**U.S. Forest Service White Paper**

# A Summary of the Groundwater Resources of the Wayne National Forest

**Troy Thompson**

**Eastern Region Regional Hydrogeologist**

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## SCOPE

The purpose of this paper is to provide baseline hydrogeological information for assessing the potential groundwater impacts of any proposed activities on the Wayne National Forest (WNF), such as the development of tight shale formations (most notably the Utica Shale). A review of the overall risks to groundwater posed by all oil and gas activities, including tight shale formation development, and possible approaches for identifying, monitoring, and mitigating those impacts is provided as an attachment to the this paper.

This review is based on a review of readily available published information on the geology and hydrogeology of the WNF area. The most significant references used are cited in this document. All conclusions are subject to change based on the discovery of new information.

## LAND STATUS

The land within the general boundary of the Wayne National Forest within the Ohio counties comprising parts of the Athens District - Athens Unit (Athens, Hocking, Morgan, Perry, and Vinton), the Athens District - Marietta Unit (Monroe and Washington), and the Ironton District (Gallia, Jackson, Lawrence, and Scioto).

## SUMMARY AND CONCLUSIONS

### Summary of Groundwater Conditions on the Forest

The essential characteristics of the groundwater system across the WNF are summarized in the bullet points below. The following sections provide more detailed information on the hydrogeology and related geology of the Forest.

- The geology and hydrogeology of the WNF will be fairly consistent across all districts and units. The only potentially significant differences will be on the most western portions of the forest where older (Mississippian age) bedrock with higher groundwater production potential may be sufficiently shallow to use as a source of water.
- Groundwater is primarily contained in a system of flat-lying, Pennsylvanian and Permian age, interbedded sedimentary rocks and altered sedimentary rocks consisting of dominantly sandstone and shale with lesser amounts of limestone, coal, and clay.
- Overlying bedrock are deposits of unconsolidated residuum (heavily weathered and altered-in place bedrock) and alluvial-fluvial (eroded and water transported) material consisting of gravel, sand, silt and clay. These deposits will tend to be thin to non-existent except along the lower valley slopes and valley bottoms. They

may contain some groundwater, but only sand and gravel deposits along or near streams in some of the larger valleys are likely to provide usable groundwater supplies. Most unconsolidated deposits will be too thin or impermeable to be used as a source of groundwater.

- Groundwater flow in the bedrock is dominantly or almost exclusively through fractures. Most of the original primary porosity in the bedrock has been eliminated by cementation. The limestone units are too thin to contain significant dissolved cavity porosity.
- The bedrock has undergone little deformation and most of the fracturing will be associated with stress release at and near the land surface. Fracture intensity will tend to decrease with depth with most fractures occurring at depths above 200 to 300 feet bgs. Fracture intensity will also vary by rock type with harder and more brittle rocks like sandstone and coal exhibiting the most fracturing, and softer or more ductile rocks like shale exhibiting less fracturing. The less fractured layers will tend to behave as barriers and divert most flow laterally. Large fractures or fracture zones will control most groundwater flow.
- The hydrogeological system does not contain discrete aquifers in a classical sense[1]. Groundwater enters the subsurface as recharge on the uplands and valley

[1] The term "aquifer" has to be used with caution as it can imply risks that may or may not exist. Many lay people assume an aquifer means a subsurface source of groundwater where the groundwater is readily connected throughout the extent of the aquifer, which implies that the introduction of contamination into one part of the aquifer inherently poses a risk to most or at least a large portion of that aquifer as well as anything or anyone that receives water from the aquifer. However, aquifers vary widely in how they contain and transmit groundwater. At one end of the scale are aquifers like the sand and gravel aquifers along the Hocking River, which generally will yield several hundred gallons of water per minute to wells drilled anywhere in them. Unfortunately, the other end of the scale is still being debated by hydrogeologists. One common definition is:

> "Rock or sediment in a formation, group of formations, or part of a formation which is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs." (Fetter, 1988, p. 565)

Another definition that avoids the ambiguity of "economic quantities" is:

> "An aquifer is a water-bearing reservoir capable of yielding enough water to satisfy a particular demand." (Driscoll, 1986, p. 19)

While perhaps a little clearer, the second definition still fails to adequately define the lower bounds of what might be considered an aquifer. It is widely recognized that some geological formation are largely unable to supply water for any particular demand, but may still contain isolated fractures sufficiently connected to a source of water to provide a minimally usable supply for a certain purpose (which may be just an occasionally used vacation residence). There is ongoing debate as to whether or not such formations should even be called aquifers.

Rather than focusing on whether or not such formations are or are not aquifers, it is more useful to look at their hydrogeologic properties and what they imply about the risks posed to groundwater supplies from contaminant releases. If the formation contains only relatively isolated water-bearing fractures or zones, this indicates that any release is likely to be confined to those fractures or zones directly impacted by the release and pose little if any threat to other sources of groundwater in that formation. The negative side of this is that such contamination is not going to attenuate very quickly leaving that local source of water unusable for a very long time. The available geological and hydrogeological information, as discussed elsewhere in this paper, indicates that the bedrock groundwater conditions, or "aquifers", that underlie the WNF are likely to have these types of characteristics and risks.

bottoms, than flows both downward and laterally in shallow fractures and porous unconsolidated materials until most is discharged to seeps, springs and surface water bodies in the valleys adjacent to the recharge areas. Some will flow to deeper depths in the bedrock but most of this will be diverted laterally and discharge to the overlying valley floor. A small quantity, perhaps only 0.5% of the original recharge, will escape this shallow flow system and travel to deeper bedrock where it will eventually cross under surface water divides and be diverted to discharge points in deeper valleys.

- Deeper zones of stagnant fossil or formation water will be encountered beneath the system of active groundwater flow. There may be some potential for this water to be drawn into the overlying flow system if that system is sufficiently disturbed, but the risk is likely low.
- Historical coal mines will significantly alter the groundwater flow system. Underground mines will tend to increase fracturing and flow in the overlying bedrock. They will then capture and divert the water to surface discharge points further reducing recharge to the underlying bedrock. They may divert shallow recharge from one watershed to surface discharge points in another. If the mines are blocked from surface discharge they may provide enhanced recharge to underlying bedrock. Surface mines may have eliminated shallow groundwater zones or have eliminated shallow materials that help filter recharge to deeper zones. They may increase recharge to underlying bedrock if they have been filled or covered with coarse material, or reduce it if they have been filled or covered with fine material. Due to spatial variations in fill materials in surface mines the groundwater flow paths through those materials may be complex and difficult if not impossible to predict.
- Natural groundwater quality will tend to decrease with increasing depth as groundwater flow rates decrease and groundwater has more time to dissolve materials from the bedrock. Consequently the shallow flow zone will have the best groundwater quality. Deeper groundwater will gradually contain more dissolved material eventually becoming brackish then saline. This may occur within a few hundred feet of the surface. Brackish water has been encountered as shallow as 100 feet below ground surface (bgs) in some places. Stagnant water, such as that found associated with petroleum deposits, will consist of brines.
- Deeper groundwater may contain dissolved materials commonly associated with anthropogenic sources but that are actually from natural sources, which may complicate the identification of releases.. These may include methane and other hydrocarbons, metals, and salts. Special analytical techniques may be able to differentiate between natural and anthropogenic sources. In most instances, collecting background or baseline samples prior to the commencement of activities with a potential to impact groundwater may be necessary to clarify contaminant sources.
- Groundwater production from the Pennsylvanian and Permian age bedrock layers underlying most of the WNF will be barely sufficient for the needs of single-family residences, typically being less than 3 gallons per minute (gpm) for a well. Water production is dependent on the well encountering sufficient fractured layers of groundwater bearing bedrock, and some wells are dry. The deeper

Mississippian sandstones underlying the far western portions of the Forest and some of the sand and gravel deposits along the larger streams on the Forest may produce groundwater at rates of 10 to 25 gpm per well.

- Almost all of the areas of the WNF mapped by the State of Ohio for groundwater pollution potential have been rated as having relatively low risk. This is due to a combination of factors that limits the ability of water at the surface to infiltrate to the subsurface. Unmapped areas of the WNF would likely have similar ratings as they have essentially the same characteristics that control water infiltration as the mapped areas. However, these ratings may not necessarily be applicable to subsurface releases of contaminants

**Conclusions**

The following conclusions related to evaluating potential threats from specific activities can be drawn from the information provided in this paper.

- While the relative risk of groundwater contamination from surface spills appears to be relatively low in most areas of the Forest, the actual risk will have to be evaluated on a site-specific basis.
- The only areas where potential spills may pose an unacceptable risk to groundwater are those overlying designated wellhead protection zones or high yielding aquifers. High yielding aquifers can be defined as those areas mapped by the ODNR as yielding 25 gallons or more per minute. These areas correspond to sand and gravel aquifers along the larger rivers, such as the Hocking River. It would probably be best to avoid surface activities in these areas. Horizontal drilling from well pads located outside these areas would allow safer access to tight shale formations underlying them.
- The estimated risk to groundwater from a surface release does not necessarily translate to the estimated risk from a subsurface release. This risk should be evaluated separately from that of a surface release based on site-specific data.
- The areas of greatest risk will be near the larger streams connected to sand and gravel deposits with no overlying fine grained material. A release in this area would quickly migrate to nearby, downgradient water supply wells using those sand and gravel deposits as a source of water, or to the stream potentially impacting associated ecosystems and flora and fauna.
- Elevation and its potential controls on groundwater flow pathways will play a key role in assessing risks to groundwater receptors. Releases upgradient of (at a higher elevation than) potential receptors may threaten those receptors. Generally, releases downgradient of (at a lower elevation than) potential receptors will not threaten those receptors. However, be aware that a release at a lower elevation could be carried upward by upward discharge of groundwater to a stream, river, or other surface discharge point.
- Any evaluation of potential flow pathways and risks to groundwater dependent receptors will have to consider the potential existence of abandoned mines and how they may have altered those flow pathways.

- Effective groundwater monitoring needs to account for site-specific variations in groundwater flow pathways and travel times. There is no standard set of locations or monitoring periods that will be effective in all situations.
- Background or baseline monitoring may be needed to adequately differentiate between natural or pre-existing groundwater contamination and groundwater contamination associated with a release from a particular activity.

## GEOLOGY

The WNF is located on what is physiographically referred to as the "Appalachian Plateau". This region is characterized by fluvially dissected, essentially flat lying sedimentary bedrock mostly overlain by unconsolidated sediments of variable thicknesses. The region is characterized by variably oriented generally narrow ridges separate by relatively deep narrow valleys. Typically sandstones and similarly resistant rocks form the tops of the highest areas and the steeper parts of the side slopes. Shales and other rocks of limited resistance tend to be found in valley bottoms and outcropping along the gentlest parts of the side slopes.

The region is geologically part of the Appalachian Basin. During the late Paleozoic era (approximately 350 to 250 million years ago) the Appalachian Basin underwent repeated depositional cycles resulting in repeating marine and nonmarine sediments in response to locally subsiding crust, fluctuating global sea levels, and variations in eroded sediments originating from the east and west of the Basin. Since then the area has experienced uplift and erosion, and formation of the current land surface.

### Bedrock Deposition, Lithology and Stratigraphy

Almost all of the bedrock exposed at the surface in the WNF consists of rocks deposited in non-marine and shallow marine environments that overlay older rock formations that are more marine in origin, and include deeper marine deposits. Due to the gentle east-southeasterly dip of bedrock in eastern Ohio towards the Appalachian Basin depositional center the oldest rocks exposed at the surface are in deepest valleys in the far western part of the WNF and the youngest rocks are on the highest ridgetops in the far eastern part. As you move from west-northwest to east-southeast across the Forest the rocks initially found on the ridgetops will be found at progressively lower elevations topographically until they become completely covered by younger rocks. Exposed bedrock in the WNF ranges from perhaps as old as Mississippian age (more than 318 million years ago) to possibly as young as Permian age (less than 300 million years ago).The following are general descriptions of the major rock groups found in the WNF. More detailed stratigraphic information, including common drillers' names for some of the bedrock units and their equivalent geological names, is provided in Figure 1.

*Mississippian Age*

Within the proclamation boundary of the WNF bedrock of Mississippian age is exposed in the deepest river valleys on the far west side of the Athens Unit (see Figure 1). While none of it may actually be exposed on NFS lands, it underlies NFS lands and may be locally used as a source of groundwater. From available information it is not clear which Mississippian age (approximately 350 to 318 million years ago) bedrock units might be exposed at the surface in the area of the WNF. Therefore, they are shown as undivided on Figure 1. The Maxville Limestone and Rushville Shale are the uppermost Mississippian age rock units but are relatively thin and discontinuous units and may not exist at the surface within the WNF. The Logan Formation underlies the Maxville and Rushville (where they are present), is approximately 200 feet thick, and is composed dominantly of sandstone and conglomerate (Camp, 2006). It is the Mississippian age unit most likely to be exposed at surface in the area of the WNF.

The Cuyahoga Formation is not likely exposed in the area of the WNF, but its Black Hand sandstone member is an important groundwater source where it is sufficiently shallow to be potable and economical to reach. This would likely only be true for the western portions of the Athens Unit and possibly the Ironton District. The Black Hand member consists of massive sandstone.

*Pennsylvanian Age*

Most, and possibly all, of the exposed bedrock of the WNF is of Pennsylvanian age (approximately 318 to 299 million years ago). The Pennsylvanian units are characterized by a distinctive cyclicity or repetition in the sequence of lithologies that compose them. These distinctive cycles have been called cyclothems, sequences, and parasequences by various investigators. A single cycle begins with a rapid shift from terrestrial conditions towards marine or near shore conditions in response to rising sea level followed by a gradual shift to terrestrial conditions as sea level falls and sediments fill in the space created by the rise in sea level. The resulting package of sediments will exhibit a general shift to more terrestrial deposits beginning with marine sediments (offshore limestone, shale, siltstone) or near shore and terrestrial deposits of sandstone (beach and stream channel), siltstone and shale (floodplain, swamp, and lake), limestone (lake), often culminating in a layer of underclay (ancient soil) and coal. Because the environments that produce these deposits were relatively small and constantly shifting laterally it cannot be assumed that a particular bed is very continuous laterally. Individual beds representing a deposit of a single lithology range from less than 1 foot to more than 10 feet in thickness.

As shown in Figure 1 the Pennsylvanian age rocks have been divided into four formally named Groups (Pottsville, Allegheny, Conemaugh, and Monongahela), although all of them retain something of the depositional characteristics identified above. The Pottsville and Allegheny Groups are mapped together on the bedrock maps in Figures 2, 3, and 4 because it is not practical to separate them at this scale. Figure 1 shows a common subdivision of these Groups. These smaller units are not necessarily formally or even universally recognized. Other subdivisions with minor variations from these also exist. Finally, Figure 1 shows common drillers' names for some of these units that may be used on exploration drillhole and water well logs.

Following is a brief summary of the principal lithologic characteristics of each of these groups. As described in the section on hydrogeology below, lithology has implications for groundwater occurrence and migration.

The Pottsville Group (grouped with the Allegheny Group on Figures 2 and 3) is exposed on the western portions of the Athens Unit and Ironton district primarily at lower elevations along valley bottoms. It is buried beneath overlying units in the rest of the WNF. The Pottsville consists mainly of sandstone and shale with lesser amounts of conglomerate and limestone and a few relatively thin and discontinuous coal beds.

The Allegheny Group (grouped with the Pottsville Group on Figures 2 and 3) is exposed at higher elevations on the western portions of the Athens Unit and Ironton district and at increasingly lower elevations becoming confined to exposures along valley bottoms on the central portions of those Districts.

The Allegheny Group contains the economically minable layers of coal in the lower Pennsylvanian, and was originally defined in western Pennsylvania on this basis (Edmunds, et. Al., 1998). The Allegheny is also more marine in origin in its lower part and consists mainly of limestone and shale. In addition to multiple coal beds it contains significant clay layers, typically as underclays or fireclays located beneath the coal beds, and deposits of iron containing minerals, that have been mined for iron ore. Sandstone occurrence in the Allegheny is relatively minor compared to other Pennsylvanian Groups.

The Conemaugh Group is primarily exposed on the central portions of the Athens Unit and Ironton District (Figures 2 and 3) where it forms the highest topographic points at the western edge of its extent and is exposed at increasingly lower elevations until it only occurs at the surface at the bottom of the deeper river valleys in the eastern portions of those Districts. It is also exposed along the parts of the largest river valleys within the proclamation boundary of the Marietta Unit (Figure 4), although probably not on NFS lands.

The Conemaugh Group is divided into two Formations – the Glenshaw Formation and the overlying Casselman Formation. The Conemaugh Group is more terrestrial in depositional environment than the Allegheny Group. Consequently it contains more sandstone and less limestone than the Allegheny Group, and is dominantly clastic (siltstone, claystone, shale, and sandstone). The Glenshaw Formation is the more marine of the two Conemaugh formations, while the Casselman is almost all terrestrial (Edmunds, et. Al, 1998). Coal beds are relatively minor in the Conemaugh Group.

The Monongahela Group is exposed on the western portions of the Athens Unit and Ironton District and primarily on the eastern two thirds of the Marietta Unit (Figures 2, 3 and 4). Within the Athens Unit and Ironton District it forms the highest topographic points at the western edge of its extent and is exposed at increasingly lower elevations until it only occurs at the surface at the bottom of the deeper river valleys in the eastern portion of the Athens Unit. On the Marietta Unit it forms the lower part of the valleys and drainages but is largely buried on the eastern third of the District. The Monongahela is entirely terrestrial in origin and is dominated by freshwater limestones and dolomites and shales with minor massive sandstones. It also contains several significant coal beds.

*Permian Age*

Due to a lack of definitive time stratigraphic markers there is some debate as to whether or not the youngest group shown in Figure 1 (Dunkard Group) is some or wholly Pennsylvanian in age or some or wholly Permian (299 to 250 million years ago) in age. However, for the purposes of this paper it is consistent with general usage it is treated as Permian in age (Camp, 2006).

The Dunkard Group is exposed on uplands of the far eastern portion of the Athens Unit (Figure 1) and over the entire Marietta Unit (Figure 4) appearing primarily on the uplands in the western portion of the District and eventually covering almost all of the surface in the eastern portion.

The Dunkard Group is divided into two Formations: the Washington Formation and overlying Greene Formation. The Dunkard Group is terrestrial in origin and both Formations consist of sandstone, freshwater limestone, and coal. The Washington Formation also contains significant shale.

**Bedrock Structural Geology**

Bedrock in the area of the WNF exhibits little folding or faulting, and the most common deformation structures are fractures related to stress release. Horizontal or low angle fractures occur coincident with bedding planes and become less frequent with depth. Vertical or high angle fractures tend to occur parallel to side slopes. However, in the central parts of the upland areas (away from the side slopes) vertical or high angle fractures will tend to have dominantly northeast-southwest and northwest-southeast trends due to regional tectonic stresses. Vertical fractures also tend to be concentrated beneath and parallel to valley bottoms (Callaghan, et. al., 1998). Figure 5 illustrates the typical fracture patterns that are likely to be found in bedrock surrounding a valley. Vertical fractures become less common with depth and likely disappear below depths of 200 to 300 feet. Fractures are not evenly spaced and tend to be concentrated in fracture zones depending on bedrock type and stress patterns. In the Appalachian Basin more brittle rocks, such as sandstone, may have more fractures than finer grained rocks, like shale (Callaghan, et. al., 1998).

The locations of some of the stream valleys in the WNF may be controlled by the presence of significant pre-existing fracture zones. While the overall stream pattern in the WNF is dendritic a number of streams, particularly on the Athens Unit, exhibit an underlying pattern of parallel directions and distinctive changes in direction that are characteristic of fracture-controlled drainage (Figure 2).

## Unconsolidated Deposits Geology

Unconsolidated deposits on the WNF consist of residuum formed from weathering of the underlying bedrock and materials transported and deposited by mass wasting and fluvial processes. The WNF is located southwest of the known extent of glacial deposition, and other then potential glacial outwash deposits in the deeper stream or river valleys, glacial sediments likely do not exist in the WNF. Unconsolidated deposits range from thin (generally 6 feet or less) or non-existent on the tops of hills and ridges and their steeper side slopes to tens to more than one hundred feet thick in the valley bottoms. The nature of the residuum is a function of the underlying bedrock but generally will have varying stone content, which will increase with depth as the residuum grades into increasingly less weathered bedrock. Transported sediments ranging from clay to boulders blanket the shallower side slopes and toe of slopes and interfinger with fluvially deposited and reworked sediments ranging from clay to gravel in the valley bottoms.

# HYDROGEOLOGY

## Natural Controls on Groundwater Occurrence and Flow

The hydrogeology of the Appalachian Plateau and the WNF is controlled by the characteristics of the sedimentary rock layers, unconsolidated sediments, and surface topography. The rock layers likely have little primary porosity (pore space between the grains) due to the presence of infilling mineralization (cementation). Consequently, groundwater is most likely contained in and travels through secondary porosity consisting of fractures. Due to the limited thickness of shallow limestone or dolomite beds, solution enlarged secondary porosity is not significant.

Effective fracture porosity may be best developed in harder but more brittle rocks like sandstone, limestone, and coal beds. Coal beds are often extensively fractured making them good sources of groundwater. Shales, clay layers, and other fine grained rocks that are relatively soft are more likely to deform ductiley rather than brittley and therefore behave more as barriers to groundwater flow.

Variations in fracture intensity between rock units mean that groundwater storage and transmission potential will tend to vary widely in the vertical direction, and that water may be preferentially channeled horizontally towards surface discharge points (see Figure 5). The downward pressure exerted by groundwater beneath the highlands may tend to force water up through the fractures beneath the valley bottoms resulting in an upward flow gradient at those locations. Most groundwater flow will be through large fractures and fracture zones which may only represent a small portion of the total fracture population.

Flow through unconsolidated sediments will be controlled by the relative grain size of the sediment with flow preferentially channeled through gravel and sand units where present. Where groundwater discharge has a strong upward component, low permeability sediments may confine the flow and create local artesian conditions.

Large-scale groundwater flow is from areas of recharge on the tops and side slopes of the hills and ridges to areas of discharge in the stream and river valleys. Localized points of discharge consisting of seeps and springs can exist on a permanent or intermittent basis on side slopes where groundwater is intercepted by fractures or a low permeability rock layer and routed to a surface discharge point. However, most groundwater discharge is directly to surface water bodies as springs or diffuse bed flow, and is not readily discernible.

The typical groundwater flow systems of the Appalachian Plateau are shown on Figure 6. Because the uppermost rock units or formations tend to consist of similar types of rocks and because of the importance of fractures in controlling groundwater flow, the WNF does not appear to be underlain by discrete aquifers separated by low permeability aquitards. Rather the groundwater system consists of what is effectively a single aquifer with different flow systems that can exchange water. All of the units from Mississippian to Permian age have been used as sources of groundwater for area water supply wells and it is not possible to make distinctions between them hydrostragraphically, even though some individual layers within these units may behave more as aquifers while other may behave more as aquitards.

The shallowest or local flow system begins at the water table and flows from the recharge areas beneath the highlands to discharge areas beneath the adjacent valleys. The boundaries and flow directions of this flow system mirrors that of the surface water system. As much as 99.5 % of groundwater flow may be through the local flow system (Callaghan, et. al., 1998). Most of the groundwater flow in the shallow flow system is through the more abundant fractures close to side slopes and highly permeable sediments on the side slopes. Some flow will be through vertical fractures beneath the centers of the highland areas. Most of this flow is eventually channeled to the adjacent valleys, where it may travel up high angle or vertical fractures beneath the valley floors to be discharged. Travel times from recharge to discharge for the local flow system may range from weeks to years.

Beneath the local groundwater flow system is a more regional or deeper groundwater flow system, which is defined by groundwater flow that travels under one or more surface water divides before discharging to a stream or river valley. It receives water that leaks from the overlying local flow system. The deeper flow system can be subdivided into additional flow systems depending on how many surface water divides the groundwater crosses before discharge. Travel times from recharge to discharge for the deeper flow system may range from years to centuries.

Below the deep flow system is a zone of stagnant water that may be thousands to hundreds of millions of years old, and is generally considered fossil or connate water. In oil and gas fields it is referred to as formation water. Much of this water is trapped in the host rock but some of it may be connected to the overlying deep flow system. It could potentially enter the active flow system if that system is sufficiently disturbed, such as by overpumping of overlying water, but the risk is likely low. Simply drilling through this zone should not affect it.

**Coal Mining Impacts on Groundwater Occurrence and Flow**

Coal mining, whether surface or underground, can significantly alter the hydrogeologic characteristics of an area. Underground mining will tend to weaken the overlying bedrock creating more fractures and possibly subsidences and, therefore, increasing groundwater recharge and flow through these rocks. This may also lead to the draining of saturated zones and the lowering of the water table that originally existed above the mined zone, particularly above areas of long-wall mining. However, this effect may be limited to water bearing zones immediately, especially above room and pillar mines, with higher water bearing zones being largely unaffected (Booth, 1986). The mines can function as highly effective conduits and/or storage units for groundwater. Because underground mines often cross natural hydrologic boundaries they can facilitate the migration of groundwater from one watershed to another. If the mine drains to the surface it can produce relatively high volume surface discharges of groundwater while reducing recharge to underlying bedrock. If discharge from the mine is blocked, groundwater will collect in the mine and the mine may provide a source of enhanced recharge to the underlying bedrock.

Surface mining may increase or decrease groundwater vulnerability depending on the effects it has on a number of hydrogeologic factors. Surface mining may remove soils and bedrock decreasing the depth to groundwater as well as decreasing the factors that mitigate migration of contaminants thus increasing groundwater vulnerability. It might also remove shallow water bearing zones that would otherwise be vulnerable to contamination. Reclamation of the mine with coarse material may create an area of enhance recharge and migration to groundwater. Conversely reclamation with fine material (i.e. with a clay cap) may have the opposite effect. Generally though, unless the mine has been reclaimed and capped groundwater flow through the fill materials or spoils is likely to exhibit varying and generally unpredictable characteristics due to the presence of areas of hidden coarse spoils that may channel groundwater flow and areas of fine spoils that may divert flows in new directions (Hawkins, 1998). Reported hydraulic conductivities for surface mine spoils in eastern Ohio range from $5.4 \times 10^{-5}$ to $1.9 \times 10^{-2}$ cm/sec and in other areas of the Appalachian Plateau from $4.2 \times 10^{-6}$ to $2.7 \times 10^{-1}$ cm/sec, which tends to approximately 100 times higher than that of the adjacent bedrock (Hawkins, 1998). Surface mining can also significantly change surface topography and affect groundwater conditions in adjacent unmined subsurface materials radically altering patterns of runoff, recharge, and overall groundwater flow from pre-mining conditions (Weiss and Razem, 1984).

Evaluating the hydrogeology of a mined area will require evaluating all of these factors to the extent possible. This will likely require obtaining copies of mine maps for underground mines (if available) to identify possible flow pathways through the mine and discharge points from the mine, if not already known. It may be necessary to estimate the direction of dip of the mine floor to estimate flow direction. As a first cut it can be assumed to be east-southeast based on regional dip. However, actual dips may vary depending on local variations in rock structure and bed thicknesses. Examining where coal beds or parallel bedrock units outcrop on a topographic map may indicate how the mine floor dips. It is a good idea to look for mine subsidences or evidence of mine subsidences downslope from a potential contaminant source.

**Natural Groundwater Quality**

Natural groundwater quality tends to be controlled by the types of rocks the groundwater flows through and the length of time it is in contact with those rocks. This is true of groundwater in the Appalachian Basin. Groundwater flowing through the shallow flow system typically does not have sufficient time to acquire significant dissolved material and therefore will be of the best quality. In addition, even at low rates of dissolution, much of the soluble material along the pathways of the shallow flow zone has likely been leached over the thousands of years these pathways have been active. Most potable wells will be developed in the shallowest zone of groundwater capable of supporting adequate flow as this will tend to be the best quality groundwater available.

In general, dissolved materials in groundwater will tend to increase with increasing depth and the water will eventually become brackish or saline and unsuitable for most if not all uses. Brackish water has been encountered within 100 to 150 feet of the ground surface in Scioto County (Raab, 1989). It is possible that a deeper zone could have better water quality than an overlying zone due to differences in bedrock and flow pathways. However, for the hydrogeological system of the WNF this situation will only be encountered in the unusual cases where water at a given depth is recharged from some direction other than the overlying rocks.

It should be noted that some contaminants commonly associated with anthropogenic activities may occur naturally at detectable levels in shallow groundwater. Some formations have elevated levels of metals such as iron or arsenic that may show up in groundwater samples at concentrations above permissible standards. In areas with deposits of oil and gas or coal there is a possibility that groundwater will contain naturally occurring, detectable concentrations of methane or other hydrocarbons. Oil and gas reservoirs commonly exhibit some leakage and it is possible for overlying groundwater to contain naturally occurring petroleum compounds, especially in areas where the reservoirs are unusually shallow. Coal beds commonly produce methane and this gas may dissolve into groundwater flowing through or above the coal bed. Another common source of methane in groundwater is biogenic methane produced by naturally occurring bacteria in the aquifer material. Biogenic methane in groundwater can be differentiated from thermogenic methane, methane produced at depth by thermal maturation of organic matter, through carbon isotope analyses. If contamination from a nearby source is suspected it may be possible to “finger-print” the contaminants to determine if they match the chemical signature of fluids from that source. However, this tends to be expensive, and is not always conclusive. Otherwise, background or baseline sampling is recommended prior to the initiation of any activity with a potential to affect groundwater quality to identify pre-existing groundwater contaminants.

Fossil water has very high concentrations of dissolved materials. It can contain high concentrations of salts, metals, petroleum-related organic compounds, and radioactive elements. This water includes the brine or formation water often produced along with oil and gas. While this deeper water is naturally stagnant, it can potentially be mobilized by over-pumping from the overlying flow system and be drawn into a well ruining it as a source of water.

**Potable Groundwater Supply**

The characteristics of groundwater available for potable water use are essentially the same for all districts of the WNF. The following information was obtained from multiple county-level sources of information on water supply. For convenience these references are listed by county under a special reference section after the formal reference section. Groundwater for potable water use in all of these areas is obtained from unconsolidated and bedrock aquifers. Unconsolidated aquifers typically offer the greatest yields and the shallowest drilling depths. Yields of up to 2,000 gallons per minute (gpm) have been obtained from sand and gravel aquifers along the larger rivers. However, yields from unconsolidated aquifers along streams on NFS lands will be much smaller due to the more limited extents of these aquifers. Wells in these aquifers typically produce 15 gpm or less from depths of 35 to 55 feet below ground surface (bgs).

As much as 90 percent of the groundwater within the WNF comes from bedrock aquifers because they are the only available source of usable water in most areas of the Forest. Most of these aquifers barely meet the definition of an aquifer for single-family residential use with typical yields of 3 gpm or less from depths of typically less than 200 feet bgs. Table 1 provides more area specific information based on the parts of the counties occupied by the WNF. While this table shows there is some variation in bedrock groundwater characteristics, it also reinforces the observation that bedrock production tends to be highly limited.

**Pollution Migration Potential**

The ODNR has performed mapping of relative groundwater pollution potential using the DRASTIC method for multiple Ohio Counties including four that include portions of the WNF. The counties are Hocking (Fugitt and Angle, 2003), Morgan (Fugitt and Jonak, 2001), Perry (Spahr, 1997a), and Washington (Fugitt, et. Al., 2002).

The DRASTIC method or mapping system is a systematic approach for evaluating and mapping the groundwater pollution potential of an area related to natural controls on hydrogeology. It does not account for the nature or source of the contaminants released into the environment or alterations to the natural environment by human activities. It contains some limiting assumptions; most notable are mapped areas no smaller than 100 acres, the contaminant has the same migration potential as water, and the contaminant is released at the ground surface and flushed into the subsurface by recharge of natural precipitation. As such, DRASTIC mapping is only intended as an initial evaluation step and will not replace site-specific evaluation or investigation.

DRASTIC derives its name from the seven natural factors that are included in its evaluations: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and Conductivity (hydraulic) of the aquifer. The area of interest is divided up into different subareas reflecting different or grouped values for each of these factors. Each factor corresponding to a particular geographic extent is given a rating and weighting. All of the factors are than combined to form a map of geographic areas, called hydrogeologic settings, each of which receives a combined numerical rating or index based on the inputs of all factors corresponding to that area.

The DRASTIC ratings for the hydrogeologic settings are only semi-quantitative and do not provide an absolute means for comparing geographic areas with significantly different hydrogeologic characteristics. However, they can be used to compare different geographic subareas within the same mapped area for relative vulnerability to groundwater pollution. They should also be useful for inferring relative groundwater pollution potential in unmapped areas with very similar hydrogeologic characteristics to the mapped areas.

Figures 6 and 7 show the DRASTIC mapping of those portions of the Athens and Marietta Units included within the mapped counties that had available GIS DRASTIC map files (Perry did not). The mapped areas are colored coded from purple (least vulnerable) to orange (most vulnerable). Each color represents a range of ratings (called indices as indicated on the map legends). Cross-hatched areas are areas not included in the DRASTIC mapping because they either represent surface water bodies or areas with significant anthropogenic impacts, mainly due to coal mining.

DRASTIC mapping defined the following seven general hydrogeologic settings in the portions of those counties within the proclamation boundaries of the WNF.

6Da - Alternating Sandstone, Limestone, Shale - Thin Regolith
6Fa - River Alluvium with Overbank Deposits
6M - Massive Sandstone
7Bf - Outwash over Massive Sandstone
7D - Buried Valleys
7Ec - Alluvium over Bedded Sedimentary Rock
7Fa - Glacial Lakes and Slackwater Terraces

Three of the general hydrogeologic settings (7Bf, 7D, and 7Fa) likely only occur along the major rivers and not on NFS lands. Copies of the descriptions, including block diagrams, of the remaining four are provided in Appendix A. Each of the general hydrogeologic settings was further subdivided into smaller areas based on a single calculated rating index.

Based on the DRASTIC mapping most of the mapped areas fall within the lowest range of vulnerability, shown in purple on the maps. This area encompasses essentially all of the upland areas above the valley floors as well as many of the most upstream portions of the valleys. The mapped areas showing increasing vulnerability that roughly corresponds with increasing proximity to the stream or river channel and with distance downstream in the drainage system. These correlations are likely a function of increased recharge due to flatter topography, increases in the amount of permeable unconsolidated vadose and aquifer materials, and decreasing depth to groundwater. There do not appear to be any differences in DRASTIC ratings that correlate with the different mapped bedrock units.

Given the strong similarity in hydrogeologic characteristics between the DRASTIC mapped and unmapped portions of the WNF, it may be possible to infer the specific DRASTIC range of indices or ratings shown on the maps that an unmapped area would fall in. Most of the highland areas above the valley bottoms likely fall within the lowest range. While it may not be possible to accurately estimate the rating range for other unmapped areas based on a simple comparison with the mapped areas, it should be possible to estimate them by referring back to the original county reports. The reports provide the methodology for calculating the DRASTIC rating, and show what values were used to calculate the DRASTIC rating for each specific hydrogeologic setting. By collecting the relevant data for an area of interest and performing the calculations, it should be possible to identify the most likely DRASTIC rating for that area.

As described in the assumptions and indicated on the maps, it is not possible to use DRASTIC to estimate groundwater pollution potential for all areas. This is particularly true for areas with significant human disturbance, such as from coal mining. It also is worth noting that the DRASTIC ratings may not necessarily reveal the relative vulnerability of groundwater to subsurface releases of contamination.

<u>Even in areas that have been mapped using DRASTIC, the DRASTIC results should only be used as the first step in gathering information on the relative vulnerability of groundwater in a specific area.</u> An area with a higher vulnerability rating will not necessarily have an unacceptable risk of groundwater contamination. But the higher DRASTIC rating could be an indicator that more effort should be put into evaluating the actual vulnerability of that area. Similarly, an area with a low vulnerability rating will not necessarily have an acceptable risk of groundwater contamination. But the rating may indicate less evaluation is necessary for that area.

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Not used due to due to the preliminary nature of work, a lack of peer confirmation (recently published), and a lack of key information needed to apply the work to management decisions. In addition, differences between the geology of the study area and the geology of the Wayne National Forest suggest the study's results may be of limited applicability to the Wayne National Forest.

\s\ Prepared by Troy Thompson
Regional Hydrogeologist, USDA Forest Service, Region 9 May 24, 2012

# ATTACHMENT A

## Figures and Table

# FIGURE 1

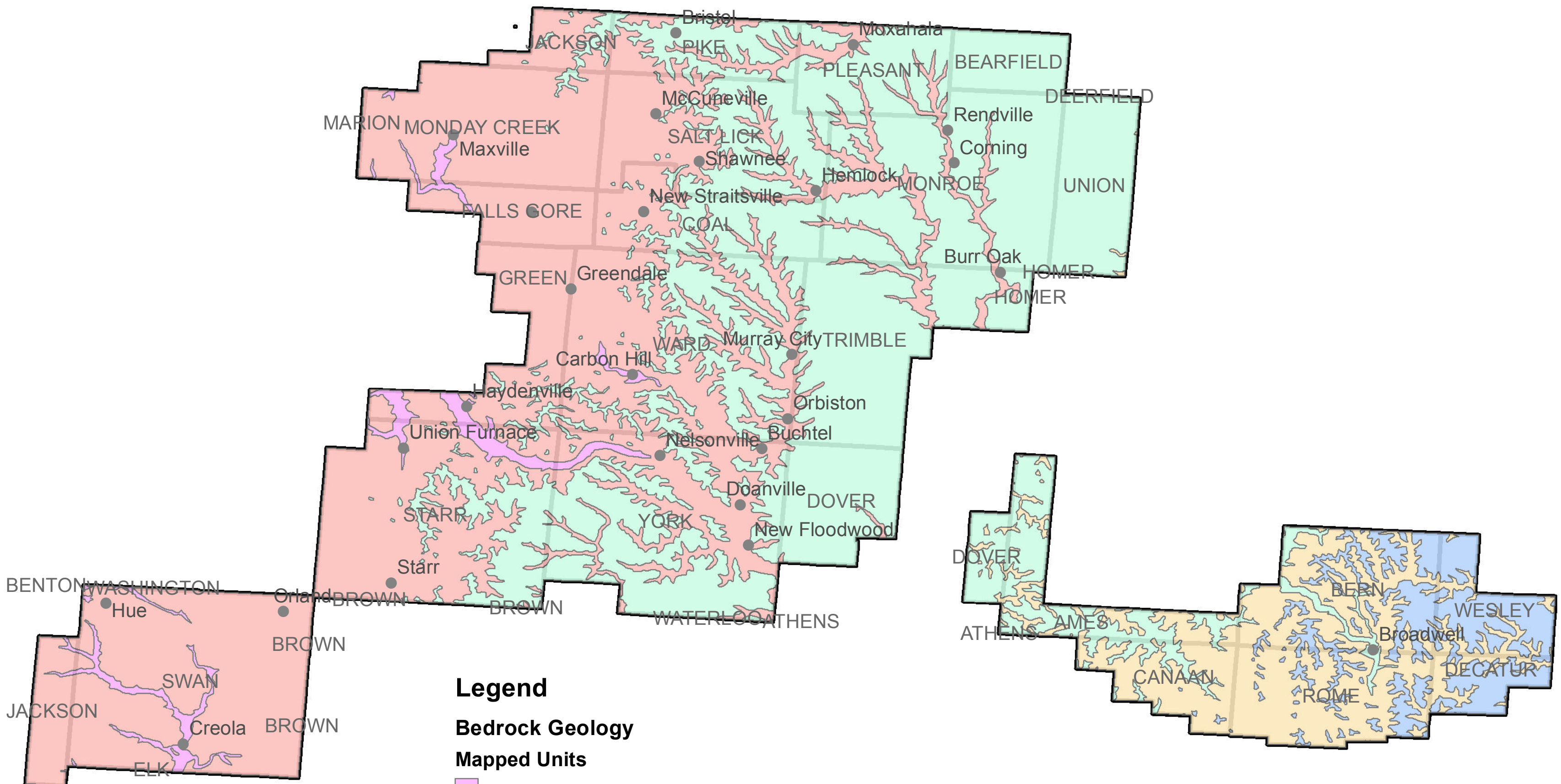
## Rock Stratigraphic Column for the Wayne National Forest

| GEOLOGIC TIME (million years before present) | TIME-STRATIGRAPHIC UNITS: SYSTEM | TIME-STRATIGRAPHIC UNITS: PERIOD | TIME-STRATIGRAPHIC UNITS: SERIES/ EPOCH | ROCK UNITS: GROUPS/FORMATIONS/ SIGNIFICANT MEMBERS OR BEDS | | | | ROCK UNITS: LOCAL/DRILLERS' NAMES |
|---|---|---|---|---|---|---|---|---|
| | PERMIAN? AND PENNSYLVANIAN | | Cisuralian? and Upper Pennsylvanian | Dunkard Group | Greene Fm | | | |
| | | | | | Washington Fm | Upper Marietta ss | | |
| | | | | | | Creston-Reds sh | | |
| | | | | | | Lower Marietta ss | | |
| 299 | | | | | | Washington coal | | No. 12 coal |
| | | | | | | Mannington ss | | |
| | | | | | | Waynesburg ss | | |
| | CARBONIFEROUS | PENNSYLVANIAN | Upper | Monongahela Group | | Waynesburg coal | | No. 11 coal |
| | | | | | | Uniontown coal | | No. 10 coal |
| | | | | | | Benwood ls | | |
| | | | | | | Upper Sewickley ss | | Goose Run |
| | | | | | | Meigs Creek coal | | No. 9 coal |
| | | | | | | Fishpot ls | | |
| | | | | | | Redstone-Pomeroy coal | | No. 8a coal |
| | | | | | | Pittsburgh coal | | No. 8 coal |
| | | | | Conemaugh Group | Casselman Fm | Summerfield ls | | |
| | | | | | | Connellsvile ss | | Mitchell |
| | | | | | | Morgantown ss | | Wolf Creek |
| | | | | | | Skelley ls | (m) | |
| | | | | | Glenshaw Fm | Ames ls | (m) | |
| | | | | | | Harlem coal | | |
| | | | | | | Noble ls | (m) | |
| | | | | | | Saltsburg ss | | Peeker |
| | | | | | | Cow Run ss | | First Cow Run |
| | | | | | | Portersville sh | (m) | |
| | | | | | | Cambridge ls | (m) | |
| | | | | | | Buffalo ss | | Buell Run |
| | | | | | | Brush Creek ls | (m) | |
| | | | | | | Rock Camp sh | (m) | |
| | | | | | | Mahoning coal | | No. 7a coal |
| | | | | | | Mahoning ss | | Macksburg 300' |
| | | | Middle | Allegheny Group | | Upper Freeport coal | | No. 7 coal |
| | | | | | | Upper Freeport ss | | Second coal run |
| | | | | | | Dorr Run sh | (m) | |
| | | | | | | Lower Freeport coal | | No. 6a coal |
| | | | | | | Washingtonville sh | (m) | |
| | | | | | | Middle Kitanning coal | | No.6 coal |
| | | | | | | Obryan ls-Columbiana sh | (m) | |
| | | | | | | Lower Kitanning coal | | No. 5 coal |
| | | | | | | Vanport ls | (m) | |
| | | | | | | Clarion coal | | No. 4a coal |
| | | | | | | Putnam Hill ls | (m) | |
| | | | | | | Newland-Brookville coal | | No. 4 coal |
| | | | | Pottsville Group | | Homewood ss | | Macksburg 700' |
| | | | | | | Upper Mercer ls | (m) | |
| | | | | | | Lower Mercer ls | (m) | |
| | | | | | | Lower Mercer coal | | No. 3 coal |
| | | | | | | Boggs ls | (m) | Salt, Upper Salt |
| | | | Lower and Middle | | | Massillon ss | | No. 2 coal |
| | | | | | | Quakertown coal | | Brill Sand |
| | | | | | | Poverty Run-Lowellville ls | (m) | No. 1 coal |
| | | | | | | Sharon coal | | Maxton Lower Salt |
| 318 | | | | | | Sharon ss/cong | | |
| | | | | | | UNCONFORMITY | | |
| | | MISSISSIPPIAN | Upper | | | Maxville Ls | | Jingle Rock |
| | | | Lower | | | Rushville Sh | | |
| | | | | | Logan Fm | Vinton Mbr | | Keener |
| | | | | | | Allensville Mbr | | |
| | | | | | | Byer Mbr | | |
| | | | | | | Beme Mbr | | |
| 350 | | | | | Cuyahoga Fm | Black Hand Mbr | | Big Injun, Squaw |

| | |
|---|---|
| Sh | shale |
| Ss | sandstone |
| Ls | limestone |
| Cong | conglomerate |
| (m) | marine zone |
| Fm | Formation |
| Mbr | Member |

AFTER: Ohio Division of Geological Survey, 1990 (rev. 2000, 2004), Generalized column of bedrock units of Oho: Ohio Department of Natural Resources, Division of Geological Survey, 1 p

# FIGURE 2
# Bedrock Surface Geology
# (Athens District - Athens Unit, Wayne National Forest)



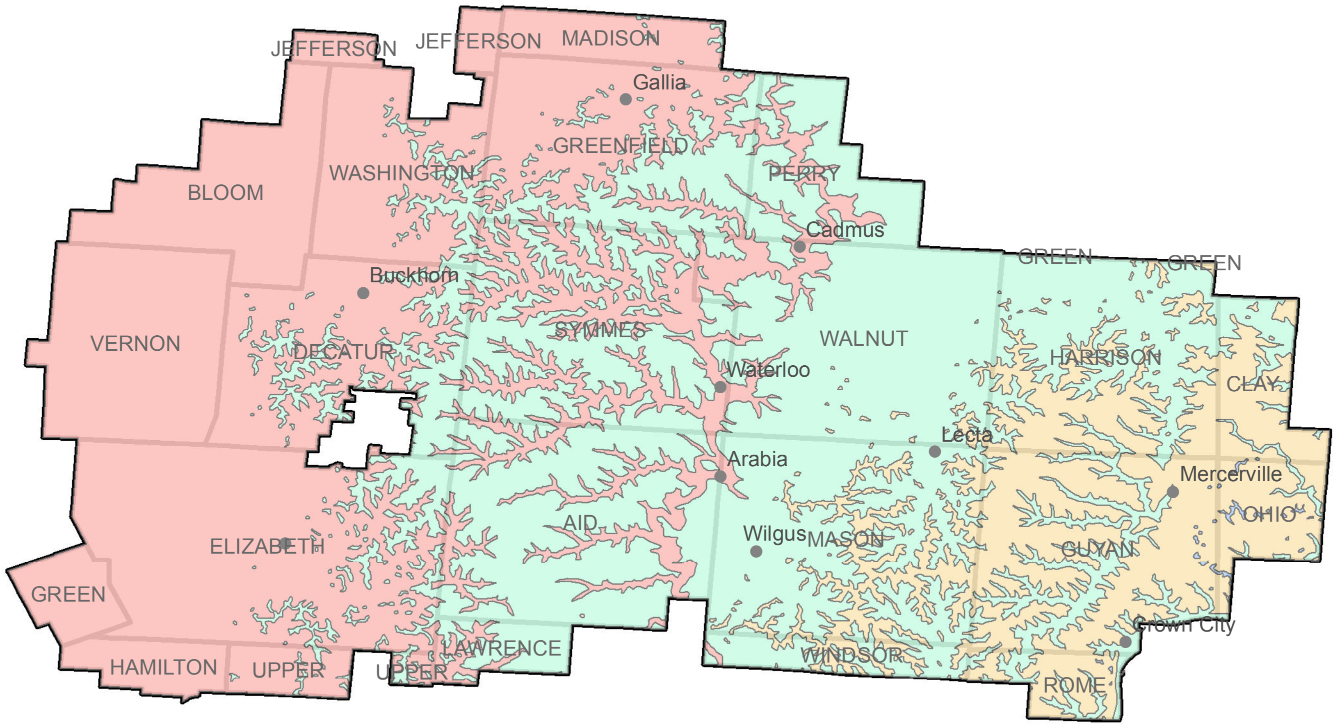

**Legend**

**Bedrock Geology**

**Mapped Units**

- Maxville Limestone; Rushville and Logan Formations, Undivided
- Allegheny and Pottsville Groups, Undivided
- Conemaugh Group
- Monongahela Group
- Dunkard Group

# FIGURE 3
## Bedrock Surface Geology
## (Ironton District, Wayne National Forest)



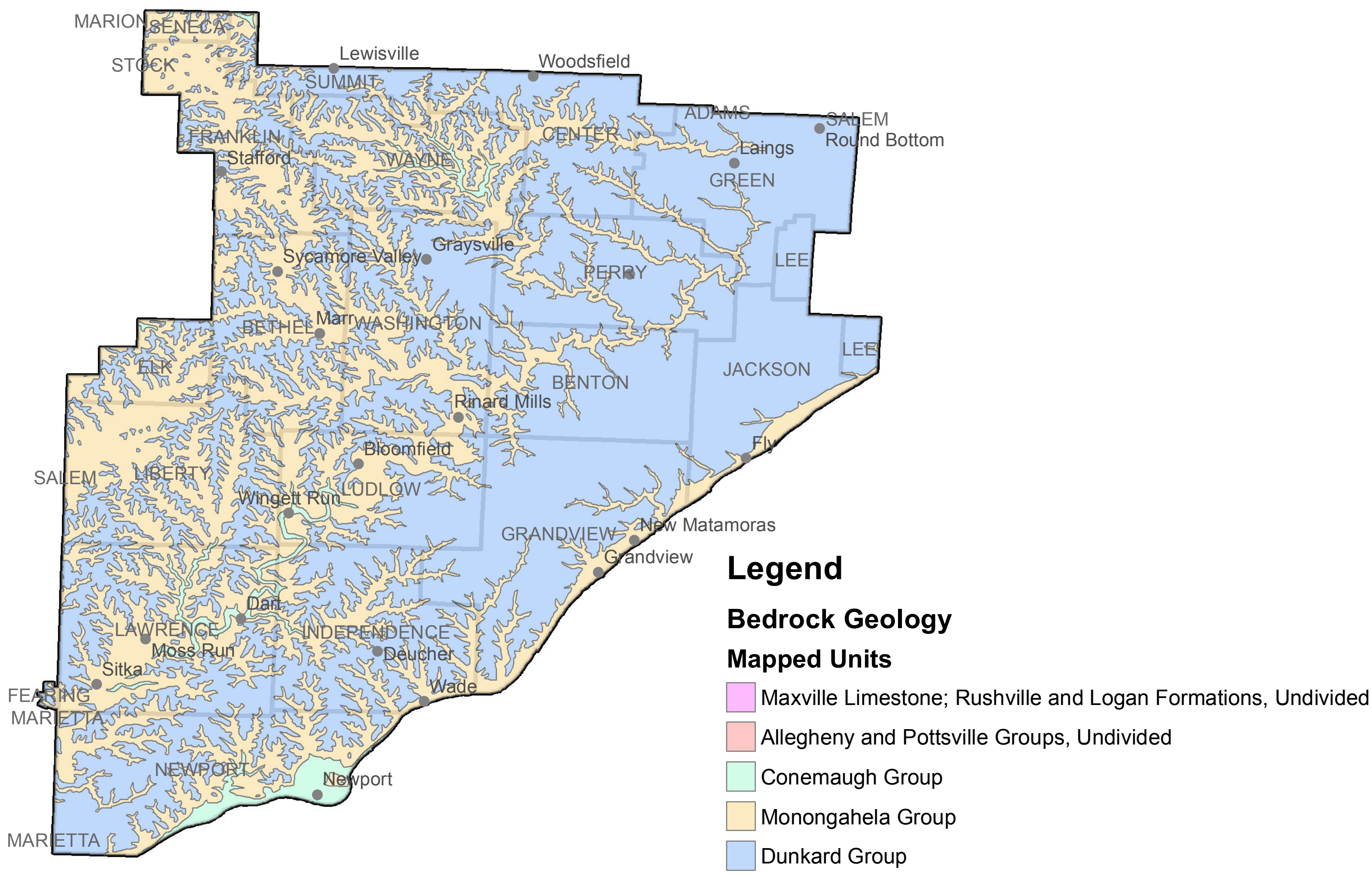

## Legend

**Bedrock Geology**

**Mapped Units**

- Maxville Limestone; Rushville and Logan Formations, Undivided
- Allegheny and Pottsville Groups, Undivided
- Conemaugh Group
- Monongahela Group
- Dunkard Group

## FIGURE 4
## Bedrock Surface Geology
## (Athens District - Marietta Unit, Wayne National Forest)



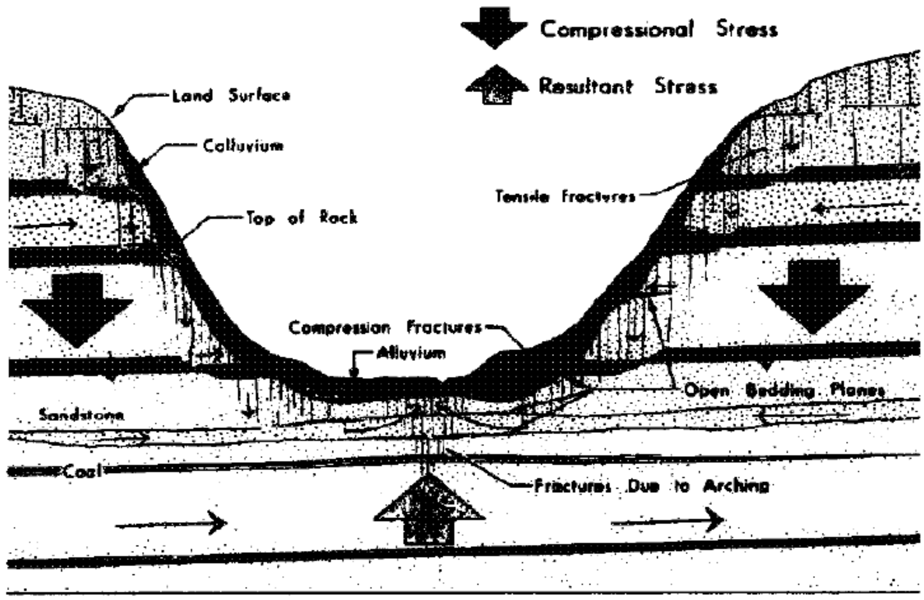
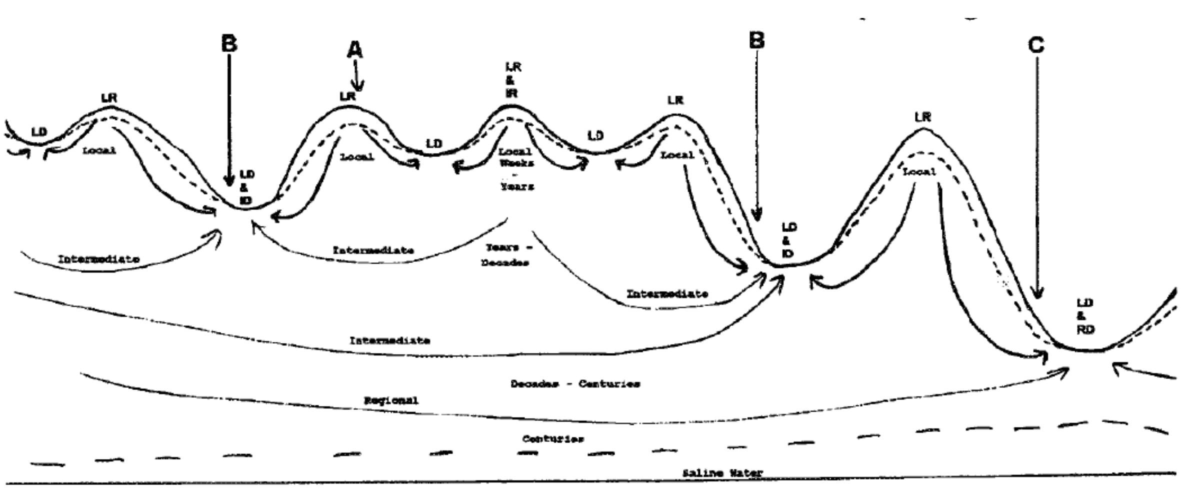



Figure 5 - Stress release controls on fracturing and resultant groundwater flow. Small arrows illustrate groundwater flow. (Reproduced from Callaghan, et. al., 1998, p. 2-15)




LR = Local Flow System Recharge Area
LD = Local Flow System Discharge Area
IR = Intermediate Flow System Recharge Area
ID = Intermediate Flow System Discharge Area
RD = Regional Flow System Discharge Area

Figure 6 – Generalized sketch of potential groundwater flowpaths ranging from local to regional scales. (Reproduced from Callaghan, et. al., 1998, p. 2-14)

# FIGURE 7
## DRASTIC Calculated Groundwater Pollution Potential
## (Athens District - Athens Unit, Wayne National Forest)

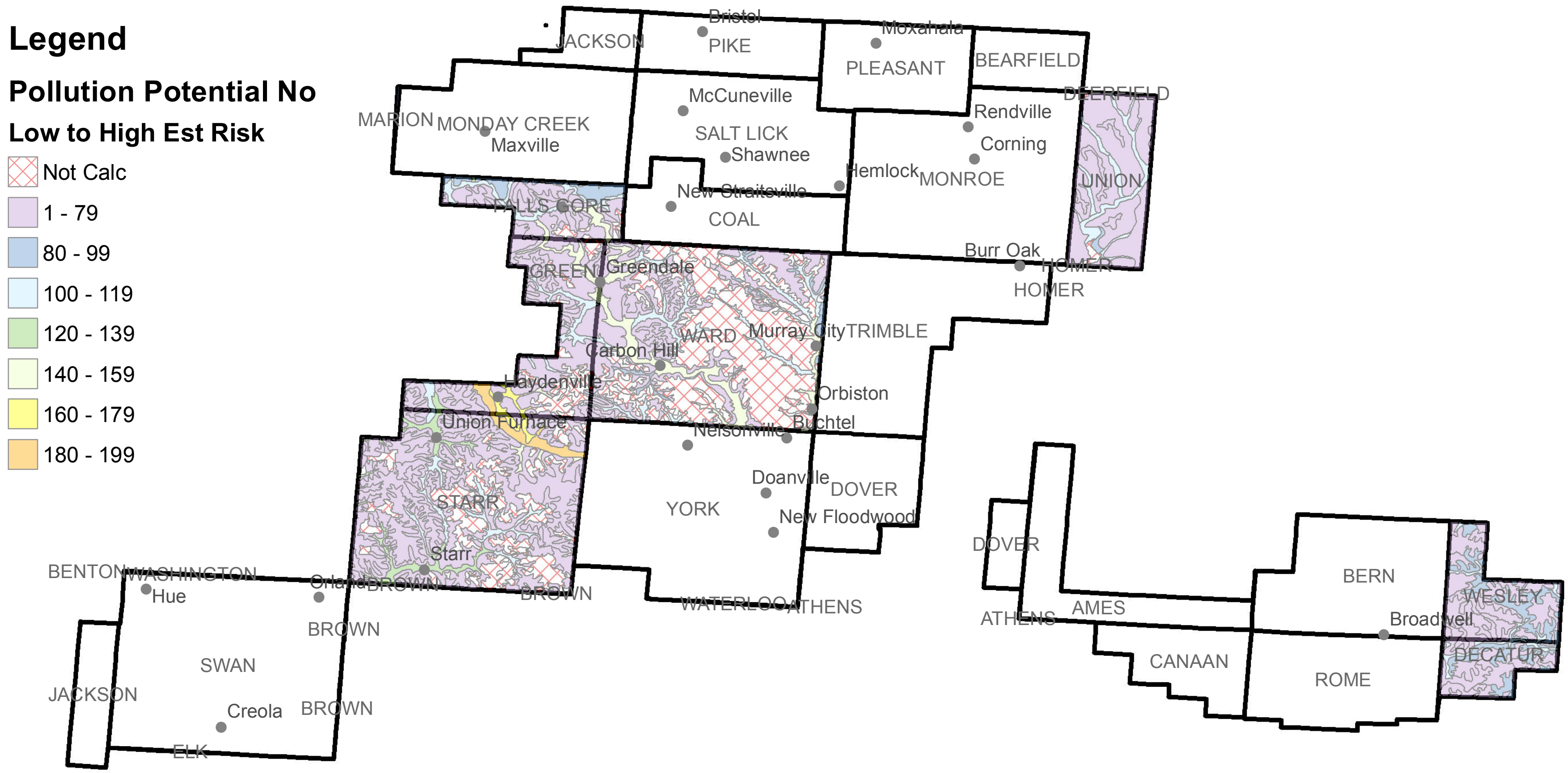


**FIGURE 8**
**DRASTIC Calculated Groundwater Pollution Potential**
**(Athens District - Marietta Unit, Wayne National Forest)**

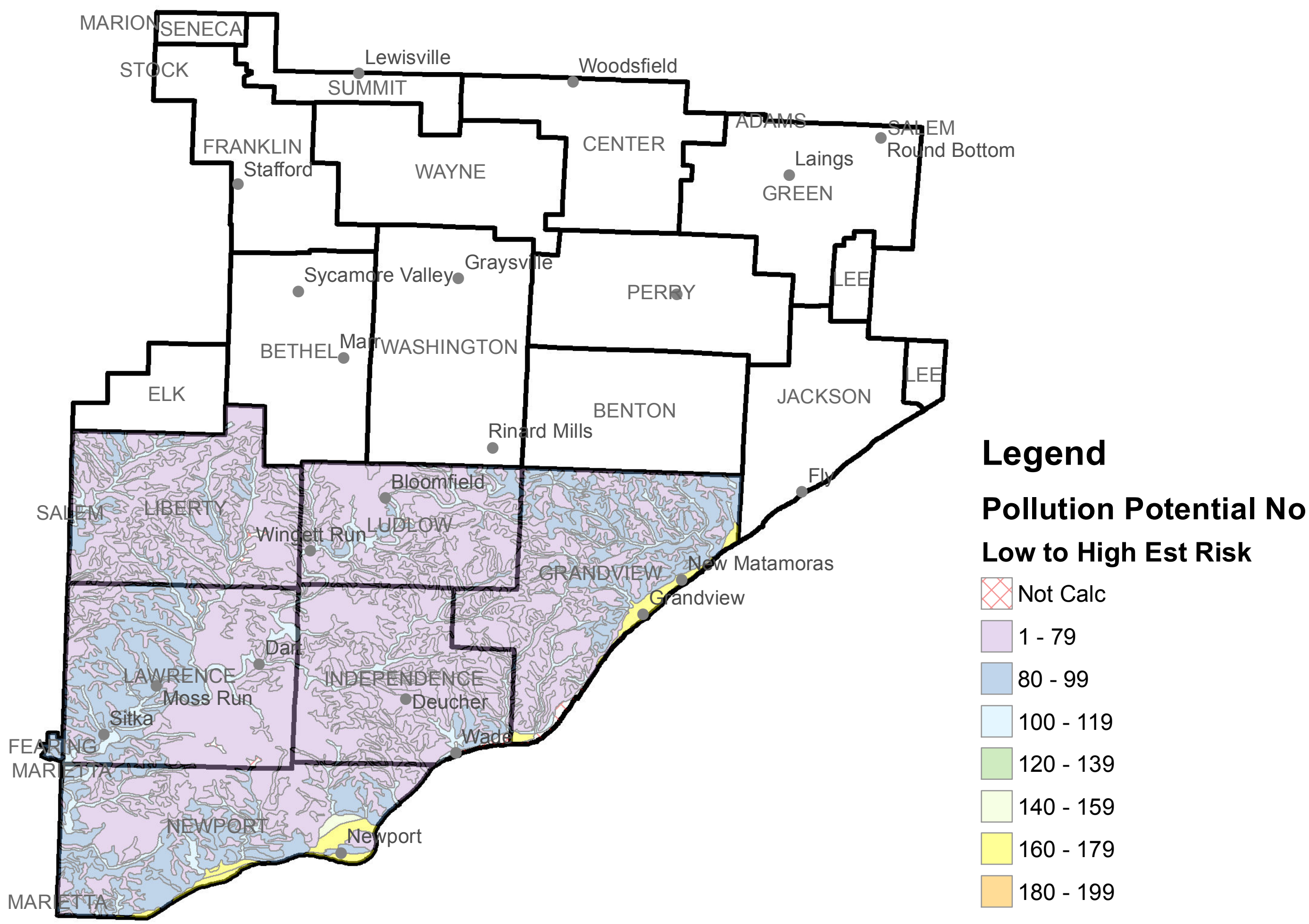


**TABLE 1**
**Summary of Bedrock Groundwater Production in Wayne National Forest by County**

| County | General Aquifer(s) | Principal Units | Well Production (gpm) | Well Ave Depth (feet) | Well Depth Range (feet) | Comments | Reference |
|---|---|---|---|---|---|---|---|
| **Athens** | Alternating layers shale and thin sandstone | Likely Allegheny and Conemaugh | <2 | NR | <125 feet | deeper drilling not recommended; dry wells common; supply may be supplemented by cisterns, spring horizons and constructed dug wells | Schmidt, 1985a |
| **Gallia** | Alternating layers shale and thin sandstone | Likely Pottsville, Allegheny, and Conemaugh | <2 | NR | <125 feet | Cisterns often used to store roof water runoff, and dry wells occur. Brackish water at depth. | Schmidt, 1985b |
| **Hocking** | Sandstones and shales | Black Hand and Pottsville | 10 - 25 | 325 | Highly Variable | | Walker, 1991a |
| | Sandstones and sandy shales | Likely Mississippian and Pottsville | 3 - 10 | 200 | NR | salt water frequently encountered | |
| | Alternating layers shale and thin sandstone | Likely Pottsville, Allegheny, and Conemaugh | <3 | 135 | NR | very limited supplies | |
| **Jackson** | Sandstone, shale, fireclay, coal, and limestone | Likely Pottsville and Allegheny | 2 | NR | NR | | Walker, 1985 |
| **Lawrence** | Alternating layers shale and thin sandstone | Likely Pottsville, Allegheny, and Conemaugh | <2 | NR | <125 feet | Cisterns often used to store roof water runoff, and dry wells occur. Brackish water at depth. | Schmidt, 1985b |
| **Monroe** | Thin beds of sandstone, shale and limestone | Likely Conemaugh and Monongahela | <3 | 110 | NR | very limited and inadequate; yields average less than 2 gpm | Walker, 1991b |
| **Morgan** | Sandstone, shale, fireclay, coal, and limestone | Likely Conemaugh and Monongahela | <3 | NR | NR | average less than 2 gpm; cistern supplies common | Walker, 1984 |
| **Perry** | Sandstones, shales, and limestones | Upper Mississippian, Pottsville, and Allegheny | 3 - 10 | NR | 30 - 400 | Drilling deeper does not necessarily increase production | Spahr, 1996 |
| | Sandstones, shales, and limestones | Upper Allegheny and Conemaugh | <3 | NR | 100 - 400 | A few wells to Pottsville and Mississippian | |
| **Scioto** | Shale, shaley sandstone, and limestone | Likely Pottsville and Allegheny | <3 | NR | NR | Brackish water at 100 to 150 feet | Raab, 1989 |
| **Vinton** | Sandstone | Black Hand | 5 - 25 | NR | Highly Variable | | Walker, 1985 |
| **Washington** | Sandstone, shale, fireclay, coal, and limestone | Likely Conemaugh and Monongahela | <3 | NR | NR | average less than 2 gpm; cistern supplies common | Walker, 1984 |

gpm - gallons per minute NR - Not Reported

# ATTACHMENT B

## Oil and Gas Activity and Potential Impacts to Groundwater Resources

All oil and gas surface and subsurface activities pose a potential threat to groundwater quality due to the contaminant-containing fluids involved in those activities. In addition, some surface oil and gas activities that do not directly involve potentially contaminating fluids can also have negative impacts on groundwater. Some oil and gas activities, such as high volume hydraulic fracturing, require or produce much larger volumes of fluids than conventional oil and gas activities. However, other than the scale of the fluid volumes involved with them, these activities do not pose any threats to groundwater not already associated with conventional oil and gas activities. Depending on how the fluids are handled even the potential threat posed by these large volumes can be effectively reduced to those associated with conventional oil and gas activities. While oil and gas-related activities are designed and normally conducted in a manner to avoid impacts to groundwater, the potential for accidental or intentional incidents that threaten groundwater remains.

Of course pointing out that oil and gas activities pose a variety of potential risks of contaminating groundwater is not the same thing as saying those risks are high. When evaluating risk it is important to distinguish between the possibility of something and its probability. Furthermore, documentation that an unwanted outcome has occurred once or even multiple times while conducting a particular activity does not necessarily prove the activity presents a high risk of that type of outcome. For example, the fact there has been multiple fatal commercial airplane crashes does not mean that commercial air travel carries a high risk of death given the extremely large number of flights completed safely every year. Similarly, data compiled from state records of violations of state regulations resulting in impacts to the environment at well sites in Ohio and Pennsylvania illustrate that such events only occur at a tiny fraction of well sites. Data collected by the State of Ohio for the 25 year time period from 1983 to 2007 shows that the actual number of active oil and gas sites with activities that result in documented groundwater contamination is only a small fraction of all such sites (Kell, 2011). This information is summarized in Table B-1. What the table does not illustrate is that the number of reported incidents at active sites per five year sub-period declined from 76 in the first sub-period (1983-1987) to seven in the final sub-period (2003-2007). This reflects in part the enactment of various new regulations addressing oil and gas activity risks to groundwater. Obviously this data only represents detected and reported incidents and the actual number is something larger. On the other hand, the potential for detecting contaminant releases to groundwater has increased as environmental investigations of property for real estate transaction purposes has grown from essentially non-existent at the beginning of the reviewed time period to routine for almost all property that has been used for commercial and industrial purposes by the end of the reviewed time period. The fact that the number of documented instances has declined by an order of magnitude in spite of increased environmental investigation activity would suggest that the number of unreported incidences is not very large.

**Table B-1**

| Phase | Number of Incidents | Number Well Sites | Percent Well Sites with Incidents |
|---|---|---|---|
| Site Preparation | 0 | 33,304 | 0.00% |
| Drilling and Completion | 74 | 33,304 | 0.22% |
| Well Stimulation | 0 | 27,969 | 0.00% |
| Production, On-lease Transport and Storate | 39 | 64,830* | 0.06% |
| Waste Management and Disposal | 26 | 83,646 | 0.03% |
| Plugging and Site Reclamation | 5 | 20,374 | 0.02% |
| Total | 144 | 83,646 | 0.17% |

*Highest number of producing wells in one year (1991). Actual number of producing wells during the 25 year timeframe was between 64,830 and 83,646. The number of wells drilled then plugged (dryholes) is not provided in the report.

More specific to high-volume hydraulic fracturing is data collected on Notices of Violation (NOVs) at Marcellus wells sites incurred from 2008 to August 2011 in Pennsylvania (Considine, et. Al, 2011). Over this time period 25 NOVs were issued for major environmental impacts resulting from activities associated with 3,533 Marcellus shale gas wells (see summary by type and year in Table B-2 below). Ten of these events would not have any different characteristics from similar events at traditional oil and gas sites. Seven of these ten involved spills of drilling muds or other fluids common to well sites, two involved releases of methane to groundwater, and one involved a fire involving gas condensate separators. While virtually any oil or gas well can have an uncontrolled release of produced fluids, in the case of the nine events with such releases, the produced fluids might have unique chemicals as a result of the hydraulic fracturing process. One of the releases arguably was as large as it was (1 million gallons) because it was a hydraulic fracturing well; but much larger releases have occurred from conventional wells. Two events involved problems with final restoration, which could occur at any oil or gas well site. However, the relatively large affected land areas associated with these two may reflect the larger size of high-volume hydraulic fracturing wellpads.

**Table B-2**

| **Major Impacts** | **2008** | **2009** | **2010** | **Jan-Aug 2011** | **2008 to 2011** |
|---|---|---|---|---|---|
| Blowouts & Venting | 0 | 0 | 2 | 2 | 4 |
| Major Land Spills | 0 | 2 | 2 | 5 | 9 |
| Gas Migration | 0 | 1 | 1 | 0 | 2 |
| Site Restoration | 1 | 0 | 0 | 1 | 2 |
| Water Contamination | 0 | 5 | 1 | 2 | 8 |
| **Subtotal** | **1** | **8** | **6** | **10** | **25** |

These impacts or violations are described as follows (Table B-3) in the SRSI report.

**Table B-3**

| Violation Type | Description | Percent all Wells |
|---|---|---|
| Blowouts & venting | Citation for a blowout or hazardous venting | 0.11% |
| Major spills on land | Citation for major (> 400 gallons) spills of materials on land | 0.25% |
| Gas migration | Citation for migration of gas in underground aquifers or substrates | 0.06% |
| Site restoration | Citation for violations of site restoration regulations | 0.06% |
| Water contamination | Citation for tainted water as the primary focus of the citation | 0.23% |
| **All Major** | | **0.71%** |

The remaining four events are arguably unique to hydraulic fracturing sites, although not necessarily high-volume hydraulic fracturing sites. Furthermore, one could argue that similar events could occur at other types of well sites and that these four events are not really unique in nature to hydraulic fracturing well sites. One well suffered a blowout due to excess pressure, which suggests that the operator overpressured the well during hydraulic fracturing or did not adequately control well pressure following hydraulic fracturing. However, it is also possible for a well to become overpressured due to natural formation pressures. Two events involved releases of hydraulic fracturing fluid, which would not be present at non-hydraulic fracturing well sites. Of course other types of fluids could be released at other sites. The other event involved the release of partially recycled flowback water. Recycling of produced water is only performed at hydraulic fracturing sites. Produced water at other sites is typically disposed of, although it might be used for certain types of well stimulation, and stored produced water at any site could be spilled or leaked.

While one event involved the release of 1 million gallons of fluid, most or all of the other fluid releases involved considerably smaller volumes which could easily be associated with traditional oil and gas sites. The other documented fluid release volumes ranged from 790 to 21,000 gallon, with most involving a few thousand gallons. Some of the release events did not have reported release quantities, and could have involved more than 21,000 gallons.

In most fluid release events the operator was able to contain or recover the release and mitigate the site to the satisfaction of PADEP officials. None of the fluid releases are indicated to have impacted water supply wells or resulted in significant groundwater contamination. Eight releases are indicated to have impacted nearby surface water bodies. Four of these are indicated to have been mitigated, while the other four are indicated to be partially mitigated or undergoing monitoring. Four releases are indicated to have impacted soil and/or vegetation, which suggests a potential to impact groundwater. They are indicated to be undergoing further assessment or mitigation. Eight releases are not indicated have resulted in specific environmental impacts, and all are indicated to have been mitigated.

Three of the five non-fluid release events did not result in direct environmental impacts. Two were failures to perform site restoration in a timely manner, which would not necessarily pose a threat to groundwater. They were mitigated. One was a fire, which did not result in environmental impacts, but required clearing of 20 acres of land to prevent spread of the fire. This land has to be restored.

Only two events are indicated to have impacted groundwater, both through the release of methane. They were considered major events because they impacted water supply wells. Both incidents are still undergoing some type of mitigation.

The primary cause for most incidents reviewed in the SUNY-Buffalo report consisted of human error including failure to follow proper procedures or maintain equipment. Seven events do not have indicated causes, although it is probable they were also due to human error or oversight. Two events are described as due to unavoidable equipment failures and no fault was assigned.

Based on the frequency or severity of the impacts the results indicate that surface storage and handling of fluids and well construction pose the greatest risk of impacts to the environment, including groundwater. Perhaps the only unavoidable causes of an event resulting in an impact to groundwater are the unpredictable breakdown of otherwise properly functioning and maintained equipment, unpredictable acts of nature, and acts or accidents caused by people not associated with well site operations.

*Surface Activities*

Surface activities during each stage of oil and gas exploration and development have a potential to impact groundwater. The threat of surface activities to groundwater will depend on how quickly and easily a release from these activities will travel to groundwater. For example, surface activities within the WNF located on upland areas could pose a threat since these are areas of recharge and commonly have little surface material to prevent, slow, or filter infiltration of surface releases. However, as shown by DRASTIC modeling, this risk will be generally low due to the limited permeability of the bedrock. However, any surface fractures in the bedrock will allow rapid infiltration of this material. This may make containment and recovery of surface spills impractical. The natural groundwater gradient in these areas is downward, which might enhance the penetration and spread of released contaminants.

Most surface releases that reach groundwater will probably be discharged to the nearby ground surface or surface water bodies as part of the local flow system. Depending on the nature of the intercepting fracture network it may be channeled through a few dominant fractures or it may be dispersed among a large number of relatively small fractures. Consequently it could emerge relatively undiluted from one or more springs or seeps, or it could be gradually discharged from a large number of points at much lower concentrations. The time to reach a surface discharge point will range from hours to months, to even years. If the contaminating material has a tendency to adhere to subsurface materials or to collect in subsurface pockets, contaminated surface discharges could last for months, years, or even decades until the residual contamination has been depleted. Depending on the concentration and nature of the surface discharges, they may not be readily noticeable but may still have significant impacts to surface water bodies and their dependent ecosystems.

Some of the contaminants that reach groundwater may be carried to deeper depths where they could contaminate existing or potential groundwater supplies. Contaminating fluids that are denser than normal water, such as production brines, will have an enhanced tendency to travel to deeper depths. Less dense fluids, such as petroleum will be more likely to be discharged to nearby surface points, although downward groundwater flow may carry them deeper.

While there are techniques for remediating contaminated groundwater, directly restoring a contaminated aquifer to potable quality is usually not technically or economically feasible. Consequently, a contaminated aquifer may be unusable for the foreseeable future unless extracted water is treated before it is used. As noted previously, some shallow naturally occurring contaminants may be encountered in groundwater.

Following is a summary of how individual surface oil and gas activities could potentially impact groundwater.

- *Non-drilling related activities*: Seismic exploration activities involving the use of explosive charges can create conditions that threaten groundwater quality. These types of activities may require drilling multiple boreholes or shot holes along a line that can stretch for several miles for the placement and detonation of explosives to create the seismic impulses that are later recorded as they are reflected back to the surface by the underlying rock formations and structures. These borings can range from 10 to more than 30 feet deep. Contamination from the explosive charge is not likely to pose a significant threat to groundwater. However, if the boreholes are not properly abandoned by filling them with low permeability material, they can function as a pathway for contaminated surface water to more quickly reach groundwater. Seismic exploration involving the use of specialized trucks (Vibroseis) that generate the seismic impulse through the mechanical vibration of metal plates on the ground surface would not to create threats to groundwater.

- *Drilling pad preparation*: Drilling pad preparation requires the clearing of vegetation and potentially surface materials from an area ranging from 0.5 acre for a conventional oil and gas well site to as much as 5 acres for a shale gas well site. Additional clearing is usually required for the construction of roads providing access to the site. This clearing may increase groundwater recharge by eliminating conditions that intercept and possibly filter surface water before it can enter the subsurface.

- *Drilling*: Drilling operations involve the use and production of various types of fluids that would likely contaminate groundwater if they were released to the ground surface. Almost all oil and gas drilling operations involve the use of drilling fluids or muds to facilitate the drilling operations. They allow the recovery of soil and rock pulverized by the drill bit and help control the flow into the borehole of subsurface fluids and gases that may be under pressure. These muds consist largely of mixtures of water and clay, such as bentonite, but may also contain chemical additives to enhance the properties of the muds. These additives may be significant groundwater contaminants if they are released at the surface and allowed to infiltrate to groundwater. For unusual conditions, such as drilling through subsurface materials that are sensitive to water, diesel fuel may be used instead of water in the muds. The use of diesel-based muds is prohibited by law if they will come in contact with freshwater aquifers. These types of muds would be used once the well has been advanced below the freshwater interval and sealed off from it. Hence their surface storage and handling would be necessary. It was not determined if diesel-based drilling muds are used in the area of the WNF. Even if they are not used now, as deeper formations are targeted for exploration and production, there is a potential they may be used in the future. A typical well will likely require thousands of gallons of drilling mud.

Once the well has reached the producing formation and been tested it may produce oil and likely will produce other formation fluids, such as high salinity water (typically called oil-field brines). These brines commonly have high concentrations of salts, and may contain high concentrations of metals and radioactive elements, as well as elevated concentrations of petroleum compounds. Depending on how the well produces, produced formation fluids may range from a few tens of gallons to thousands of gallons.

All of these fluids require surface handling and storage during use or following production. They may be stored in tanks. Large volume fluids such as drilling muds and formation fluids may be stored in lined surface pits if allowed by regulations. Fluids stored in tanks are less likely to threaten groundwater due to their relatively small volumes and the relative ease of detecting leaks. Conversely surface pits may pose a significant threat to groundwater as they can allow the release of a large volume of fluid to the subsurface before the release is detected or the pit is emptied and filled in. All of these fluids typically require transport to and/or from the drill site in tanker trucks, each of which could be the source of a release that could impact groundwater on the drill site and along the road to and from the well site.

- *Conventional Oil and Gas Production*: If the well is completed and operated as a production well it will continue to produce fluids such as oil and formation fluids with a potential to impact groundwater if they are released at the surface. As previously discussed these fluids will require handling and temporary on-site storage in tanks or pits and eventual off-site transport. Occasionally, the well will likely have to be reconditioned (worked-over) to maintain its productiveness. This may involve the temporary storage of special work-over fluids and their waste products, which can contain materials that could contaminate groundwater if they are not handled or stored properly at the surface. Depending on how the well produces and whether or not it is treated these fluids may range from only a few tens of gallons a month to hundreds of gallons a day.

- *Typical Enhanced Oil and Gas Production*: Some wells may be treated with specialized fluids to better mobilize the movement of oil and gas to the well bore. This may involve the injection of oil-field brines or other specialized fluids in some wells to drive oil or gas towards an extraction well, or the injection of fluids at high pressure to hydraulically fracture the formation. Typically these fluids are not recovered except to the extent they are forced back to the well by the temporary increase in subsurface pressure created by the injection or be produced along with the oil and gas. The surface handling and storage of these fluids and their waste products poses the same threat to groundwater as those discussed above. The volumes of these fluids will typically range in the hundreds to tens of thousands of gallons. These methods have been used for decades and so their relative risks are well known.

- *High Volume Hydraulic Fracturing*: Wells completed in a tight shale formation, such as the Utica or Marcellus shales, for gas or oil recovery will have to be treated with specialized hydraulic fracturing fluids to generate the necessary fracture porosity in the formation to allow recovery of economic volumes of gas. This will involve the injection of specially designed fluids into wells drilled horizontally into the formation to maximize well bore exposure to the formation. These fluids are made up of mostly water, but also typically contain sand to prop open the new fractures and a variety of chemical additives to give the fluid certain necessary properties. These additives can include hazardous materials such as various petroleum compounds, acids, methanol, ethylene glycol, and biocides.

  There is considerable controversy over the relative safety of the hydraulic fracturing fluids with respect to groundwater. The petroleum industry maintains that the concentrations of hazardous materials are too low to pose a significant threat to groundwater. Others worried about potential environmental impacts argue that the large quantity of additives (thousands to tens of thousands of pounds) used in each hydraulic fracturing operation pose an imminent threat if they are released to groundwater. The large volume of these fluids required for each well (1 to 6 million gallons) means that the truth is of more than academic interest. Also, the large volume of fluids used for horizontal well hydraulic fracturing, typically two orders of magnitude or more greater, is what distinguished high volume hydraulic fracturing from more traditional hydro-hydraulic fracturing. In March of 2010 the U.S. Environmental Protection Agency announced a new study to further assess the potential impacts of hydraulic fracturing on groundwater (U.S. EPA, 2010).

  Some hydraulic fracturing fluids are diesel fuel rather than water-based, and their surface release would pose a significant threat to groundwater. Based on a 2003 agreement between the industry and Congress, these fluids are not supposed to be used in conditions where they could potentially impact water supplies. However, some instances of their improper use have been documented (Soraghan, 2010).

Even if the original hydraulic fracturing fluids are handled in such a way that they do not cause an impact to groundwater, they can cause an impact after they are recovered from the well because of the materials they may pickup from the producing formation (i.e. salts, metals, radioactive elements). Commonly about one-tenth to one-third of the hydraulic fracturing fluids are recovered from each well. The surface handling and storage of these fluids and their waste products poses the same threat to groundwater as those discussed above. The potential risk they pose from release can be minimized by storing them in above ground storage tanks rather than large storage pits. If tanks are used, the amount of fluid at risk of release is that primarily that contained in one tank (generally 10,000 to 20,000 gallons). Therefore, the risk to groundwater from storage of fracking fluidsuse of storage tanks at high volume hydraulic fracturing sites can be mostly reduced to that at conventional oil and gas sites by the use of aboveground storage tanks. Disposal of these waste fluids is of particular concern if disposed nearby. However, disposal risk at the well site is reduced to that associated with transporting them to an outside disposal facility.

- *Site Restoration*: Following completion of drilling activities the drill site undergoes either partial or full restoration depending on whether or not the well was completed as a producing well. When the producing well is abandoned the site undergoes full restoration. How the site is restored can have potential impacts to groundwater if restoration results in enhanced or degraded recharge potential. If it results in enhanced recharge, especially if surface pits are not properly filled, it can increase potential infiltration of contaminated water. This will be an increased risk if contaminated surface materials such as soils or fill materials are left in place.

  Alternatively, surface restoration could result in decreased groundwater recharge if finer grained materials are imported as surfacing materials or if the existing surface materials are compacted. While the impact of this may be negligible for small drill sites, it could potentially be significant if there is a large number of drill sites spread across a recharge area. A large drill site could conceivably impact discharge to a nearby surface discharge point.

  Any site that has been used for petroleum drilling, even if considered successfully restored, may be viewed as potentially contaminated by future purchasers or users of the land. This view is not unique to such sites. Any site formerly used for activities involving more than incidental quantities of petroleum or chemicals will be viewed similarly.

*Subsurface Activities*

All subsurface activities have a potential to impact groundwater. However, the mechanism for this risk is the same for all activities: the potential for the well borehole to act as a conduit for contaminant bearing fluids to enter into a freshwater aquifer or zone. As discussed above, most discharges to shallow groundwater will likely be transported in the local flow system to local surface water discharge points. Discharges to deeper groundwater will likely reach a discharge point eventually. However, the time required for this is so long that these impacts are effectively considered to be aquifer contamination problems. These deeper discharges pose the greatest challenge to address once they occur due to the time it will take the contaminants to migrate to a discharge point and the impracticality of removing them through active remediation.

Following is a summary of how individual subsurface oil and gas activities could potentially impact groundwater.

- *Non-drilling related activities*: Non-drilling related activities, such as seismic exploration, will not have subsurface components (except the shallow drilling for seismic shot holes discussed above). Therefore, there is no further risk to groundwater posed by these activities.

- *Drilling pad preparation*: Drilling pad preparation does not involve subsurface activities. Therefore, there is no further risk to groundwater posed by these activities.

- *Drilling*: Drilling operations involve advancing a borehole through freshwater bearing aquifers to the targeted oil or gas formation. Unless proper procedures and techniques are followed to seal off the freshwater aquifer from the borehole there will be an unacceptable risk of contaminating fluids traveling along the borehole and entering the aquifer. As discussed above these fluids can include drilling mud and formation fluids.

  While drilling mud can potentially contain components that could contaminate groundwater, initially at least, the mud used is formulated to have minimal impact on groundwater quality. In addition, the mud forms a "mudcake" on the side of the borehole that initially helps to seal off encountered aquifers.

  To protect groundwater long-term the normal and legally required practice is to install various types of casing as the borehole reaches certain depths or changes in geological/hydrogeological conditions. Each type of casing is set inside the previously installed one. Typically the initial casing is the conductor casing which is set through soils and other near surface materials that may cave into the borehole. Surface casing is set from the ground surface to below the lowest groundwater zone as specified by regulations. Depending on regulatory requirements and subsurface conditions below the groundwater zone, intermediate casing may be set next. Once the target zone is reached production casing is set to the top of or into the producing formation. With the exception of conductor casing (casing set through unconsolidated material above bedrock to keep it out of the wellbore) and perhaps production casing, after each type of casing is set cement is pumped up between the casing and the walls of the borehole (the annular space) to create an annular space seal. Under Ohio regulations production casing is only required to be cemented in place where it crosses a subsurface interval with characteristics (i.e. corrosive fluids) that could degrade the casing and cause it to fail and leak or that have an enhanced potential for causing fluid migration along the outside of the casing.

Improper placement of the annular space seal or cement is the main cause of leaks of well fluids into freshwater aquifer zones. There are methods for testing the integrity of an installed seal, but unless required by regulation, those tests are not always run. Leaks of well fluids can also occur if there is a casing defect that causes it to fail. However, the chances of this occurring in a way that impacts groundwater is small given that there are typically at least two sets of casing across the groundwater zone.

- *Conventional Oil and Gas Production*: The potential for well fluids in the well to impact groundwater during oil or gas production depends on the whether or not the casing and annular space seals remain intact. Typically this is not a problem. However, degradation or corrosion over time of the casing or annular space seal can create leaks or pathways allowing fluids to reach groundwater zones. Unfortunately, there is no readily apparent way to identify when this has occurred.

- *Typical Enhanced Oil and Gas Production*: The activities conducted during enhanced oil and gas production can increase the potential for leaks of well fluids into an aquifer. The uses of certain types of fluids that may be chemically corrosive and the potential application of elevated pressures increases the risk of failure of the casing or annular space seal. Usually this failure is not readily apparent unless it is so large it noticeably affects the well treatment activities. Monitoring of groundwater conditions outside the well may be required to detect releases. The state recommends but does not require monitoring of nearby water supply wells for potential impacts from releases. Installation of groundwater monitoring wells specifically for detecting releases is typically only performed when a release is suspected. Installation and sampling of monitoring wells can be costly and requires special expertise, which is why it is not routinely performed.

- *High Volume Hydraulic Fracturing*: The integrity of the casing and annular space seal is even more important for a well undergoing hydraulic fracturing then it would be for conventional wells since the hydraulic fracturing fluid is pumped into the formation under high pressure. However, because a casing or annular space seal failure would be costly to the operator in terms of lost hydraulic fracturing fluid and wasted time, money, and effort, the casing and seal should be installed with greater care and quality materials and more attention be paid to verifying that the casing and cement seal have been properly installed prior to performing the hydraulic fracturing operation. Furthermore, even if the casing is breached the amount of fluid that will enter the formation surrounding the wellbore will be limited by the permeability of the formation. Available information for the WNF indicates that most formations containing potable water have low permeabilities and therefore would not be able to accept a large volume of leaked fluid unless the casing breach was not repaired for a very long time. Therefore, it cannot be said that a tight shale well will necessarily have a greater potential for a well construction failure that will pose a threat to groundwater quality than a conventional oil and gas well would.

Because the shale formation is fractured by pumping the hydraulic fracturing fluid into it under high pressure, many people have expressed concerns that this process could create pathways through the overlying rock layers that would allow contaminating fluids to reach overlying groundwater aquifers. In addition, some geologists have expressed concerns that the process could force injected fluids and existing natural brines into permeable fault and fracture zones that extend upward to the potable groundwater aquifers (Myers, 2012, USGS, 2012)[2].

However, these conjectures are hypothetical, require more research, and, based on existing information, do not necessarily indicate a significant risk from hydraulic fracturing. The USGS (2012) expressed concerns that the State of New York's review of the potential impacts of hydraulic fracturing on groundwater underestimate the number of fault and fracture zones that could potentially behave as permeable conduits for hydraulic fracturing fluids and expelled formation fluids to travel to shallower potable groundwater aquifers. While the USGS shows that the number of fault and fracture zones is greater than those reported by the State of New York, the potential that such features will function as permeable pathways is uncertain. Fault and fractures zones may function as permeable pathways, but they may also be closed up and function as barriers to flow due to existing lithostatic pressure or the presence of infilling materials such as fault gouge or precipitated minerals. Conditions favoring closure of these zones are increasingly likely to occur with depth. It is not at all certain that the induced pressures of hydraulic fracturing will be sufficient to open these zones over the depth ranges required to permit fluid flow to overlying aquifers. Myers performed interpretive modeling that suggests hydraulic fracture fluids and formation brines could be forced into an up permeable faults or fracture zones and into overlying potable groundwater aquifers. Myers' modeling is based on a highly simplified modeling approach, and because of its recent release has not undergone formal review and response by the scientific community. Some of the assumptions underlying Myers' modeling and conclusions are not at all certain. It assumes the existence of fault or fracture zones with enhanced permeability relative to adjacent rock extending from depths of several thousand feet to those of overlying aquifers. Myers also postulates the existence of a natural upward vertical flow gradient between these depths and the surface. Since water does not naturally flow against the force of gravity such a natural gradient would either require the existence of over-pressured conditions at depth in permeable contact with unconfined conditions near the surface over time scales of thousands or millions of years, which seems unlikely, or a regional groundwater flow regime driven by recharge in an area of higher surface topography and extending to

[2] While not a threat to groundwater concerns have also been raised that injection of fluids by hydraulic fracturing into fault zones could induce damaging earthquakes. The available evidence and what is known about the processes of earthquake generation indicate this is highly unlikely. This subject is reviewed in Thompson, 2012.

depths of several thousand feet. Given the relatively low relief of the shale gas producing regions of the eastern United States, particularly eastern Ohio, this does not appear to be likely and would require considerably more research to prove.

Several other lines of evidence indicate the potential for fluids to travel from the zone of induced fracturing to overlying aquifers is low.

- While hydraulic fracturing fluids are injected under what are called high pressures these do not necessarily represent a large increase in the pressure of the target zone for fracturing relative to existing subsurface pressure. The zone of fracturing is already under high natural pressures as the result of lithostatic stresses. The pressure of the injected fluids does not directly induce fracturing but rather causes an incremental alteration in the balance of natural lithostatic stresses, which in turn induces fracturing of the rock (Hubbert and Willis, 1972). Horizontal wells for hydraulic fracturing are not drilled in a wagon wheel spoke pattern from a central location but instead are oriented in the direction that takes maximum advantage of the natural lithostatic stresses. Hubbert and Willis point out that in most regions subsurface conditions appear to exist in a condition near the breaking point of the rocks, which suggests that the increase in subsurface pressure associated with hydraulic fracturing is only a fraction of the already existing hydrostatic pressure.

- Typical hydraulic fracturing pressures are actually less than those produced to inject fluids for disposal into subsurface zones. Furthermore the volumes of fluids injected into waste disposal wells are much greater than those injected in high volume hydraulic fracturing wells and the fluids travel much further from the wellbore. However, even though there are more than 150,000 deep injection wells in the United States (USEPA, 2012) and deep injection has been ongoing for decades, contamination of overlying aquifers has not been shown to be a significant problem.

- The existence of deposits of oil and gas in geologic formations above the shale gas formations indicates there is not a ubiquitous presence of permeable pathways between overlying aquifers and these deeper depths. The oil and gas deposits formed 10s if not 100s of millions of years ago. Because petroleum is lighter than water and water already fills any available pore space not occupied by petroleum, they would have escaped to the surface long ago if they were in contact with any kind of permeable pathways. While such pathways could conceivably exist in areas between petroleum reservoirs the existing evidence does not indicate it, and much more research would be required to do so.

- Many conventional oil and gas reservoirs or traps are formed by faults offsetting low permeability formations against the formation containing the reservoir. Many of these faults extend to shallow depths. The fact that oil or gas in these reservoirs has not escaped along these faults proves they are barriers to flow rather than conduits.

- For decades hydraulic fracturing has been conducted at considerably shallower depths than those at which it would occur beneath the WNF without documented instances of impacts to overlying aquifers[3]. Obviously the potential for hydraulic fracturing to cause fluid migration to overlying aquifers will increase the shallower the hydraulically fractured zone and the closer it is to overlying aquifers. For example, according to the Michigan Department of Environmental Quality (MDEQ, 2011) since the 1960s more than 12,000 wells have been hydraulically fractured with no documented impacts to the environment. Most of these wells have been completed in the Antrim Shale. Typical production in the Antrim Shale is from depths of 1,200 to 2,000 feet (Dolton and Quinn, 1996), which is considerably shallower than the depths of the Utica or Marcellus shales in Ohio.

Overall it is quite striking that even though hundreds of thousands of wells have undergone hydraulic fracturing in the United States over the last several decades there are no documented instances of the injection of hydraulic fracturing fluids into the target zone causing impacts to overlying aquifers. Those instances of documented groundwater impacts related to well sites undergoing hydraulic fracturing have been attributed to releases of the fluids at the surface or problems in well construction that have allowed fluids to escape to shallow depths. While there may be unreported known incidences or incidences that have never been identified, the lack of documented incidences suggests these are relatively few relative to the large number of wells that have been hydraulically fractured.

It is possible that hydraulic fractures could intersect a nearby well that is improperly abandoned or constructed allowing the hydraulic fluids to travel up

[3] Limited instances of hydraulic fracturing fluid or chemicals contained in those fluids have been documented in groundwater aquifers (DiGiulio, et. Al., 2011 USEPA, 1987) but they do not prove the fluids migrated into the aquifers as a result of the hydraulic fracturing process. DiGuilio et. Al. detected hydraulic fracturing-associated chemicals in groundwater supply wells located in the vicinity of natural gas wells that had been hydraulically fractured in the area of Pavillion, Wyoming. While it is possible these chemicals migrated from the hydraulically fractured zone, the site is not analogous to those undergoing hydraulic fracturing of the Marcellus or Utica shales. At the Pavillion site the aquifer and the zone of fracturing were relatively close (as close as 600 feet) with no apparent geological barriers to migration between the two. Furthermore, DiGuilio, et. Al. show evidence that improper well construction could have created the migration route. The USEPA reports that in 1982 a private water supply well in West Virginia was contaminated by hydraulic fracturing fluid following hydraulic fracturing of a nearby gas well. The USEPA report notes that this was attributed to a failure of the hydraulic fracturing process (not specified or explained in the report). The report also notes the gas well only had cemented casing to 30 feet below the freshwater zone, which was in compliance with then existing state requirements. Therefore it is not clear if the problem is related to injection causing the hydraulic fluids to escape the injection zone, or a lack of adequate cemented casing to prevent hydraulic fluid from traveling up the well bore to fresh groundwater. A review of the incident by the Environmental Working Group (Horwitt, 2011) suggests that the fracturing may have intercepted one or more nearby gas wells drilled to the same or greater depths, which then allowed the fluids to travel upwards into the fresh water zone.

the wellbore. Presumably it would it would take a "highly improbable" combination of four factors for this to occur: 1) hydraulic fracturing would have to induce fractures sufficiently far to reach a nearby well, 2) because fractures tend to spread in one direction that well would have to be located in the right direction from the fractured well, 3) the old well would have to be improperly plugged, and 4) the fluid would have to have been injected with enough force to drive it up the old wellbore (Horwitt, 2011). All of the traditional producing formations underlying the WNF are shallower than the Utica Shale reducing the chance of fractures intercepting them during hydraulic fracturing of that unit. Other potential tight shale formations, such as the Marcellus Shale, are shallower than some of the producing formations, which indicates a greater potential for hydraulic fracturing of them to intercept other wellbores. While incidences of fracture interception of pre-existing wells have apparently occurred (see Horowitt, 2011) it does not appear to be a common or at least a confirmed source of groundwater contamination.

If the State of Ohio regulators would allow the use of onsite groundwater as a source of water for hydraulic fracturing operations, there might be a concern about potential impacts to the local groundwater supply. As noted previously a single hydraulic fracturing well will require from 1 million to 6 million gallons of water. Although for each well this represents a single use, it does not appear likely that hydraulic fracturing operators will be able to obtain sufficient water from groundwater beneath the WNF. Known water supply wells in the upland areas of the WNF almost all produce at low rates (3 gpm or less) and would be insufficient for providing water for hydraulic fracturing operations. There may be previously unidentified groundwater zones at greater depths that could produce sufficient water, but this would have to be verified. The potential for obtaining water from deeper depths will be further limited by increasing salinity levels, which may make the water quality unacceptable for hydraulic fracturing fluid. The only other groundwater alternative would be to obtain water from a well constructed near or at least within the valley of a river or larger stream. However, state water law might limit or prohibit the transfer of water from parcel of land to another.

If a hydraulic fracturing operator attempts to obtain hydraulic fracturing water from groundwater supplies, the greatest threat will be temporary impacts to nearby surface water bodies or water supply wells. These groundwater receptors may experience a decrease or even total loss of water, although they should recover once pumping for the hydraulic fracturing operation is completed. However, for groundwater dependent ecosystems these impacts could cause serious, long-lasting problems depending on how long they are deprived of groundwater discharge.

- *Site Restoration*: The only subsurface activity involved in site restoration is abandonment of the well. This consists of filling the well with a sealing material, such as cement, to prevent formation fluids traveling through the well and into a groundwater zone. Even with properly installed casing and annular space seals, a well that is left open will eventually pose a threat to groundwater as those components will undergo degradation and corrosion. Well abandonment is now regulated by the State and conducted according to well established industry practices. Therefore, recently abandoned wells will become sources of groundwater contamination in only rare instances.

However, it cannot be assumed that wells were properly abandoned prior to the implementation of applicable regulations or the development of common industry practices. Because the WNF is located in an area that has had oil and gas activity for many decades, there may be many wells that were not properly plugged when abandoned. Furthermore, many of them may not have been constructed with adequate casing and annular space seals. Some of these could now, or in the future, be conduits for formation fluids to contaminate overlying aquifers. Unfortunately, records or knowledge of the locations of these wells has often been lost. Furthermore, in an area like the WNF where groundwater supply wells are sparse, their impact on groundwater supplies may not even be noticeable until those supplies are tapped.

## RECOMMENDATIONS

Table B-4 in Attachment B lists relative risks posed by different oil and gas activities to groundwater on WNF lands and associated potential Forest Service actions for addressing those risks. The activities are listed in relative order of potential risk from highest to lowest. Special emphasis is placed on how risks may relate to tight shale formation wells.

## REFERENCES

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## Table B-4 - Relative Risks to Groundwater from Oil and Gas Activity (from greatest to least)

| Activity | Potential Risk | Potential Forest Service Actions |
|---|---|---|
| Recovered fluid handling | All oil and gas wells are likely to produce recovered fluids besides petroleum, such as oil field brines. Wells undergoing enhanced recovery will also have recovery of fluids injected as part of the enhancement activities. For tight shale wells approximately 1/10 or more of the hydraulic fracturing fluid injected into the formation is recovered following hydraulic fracturing; this would potentially amount to more than 1 million gallons of recovered hydraulic fracturing fluid. These fluids may not only contain the chemicals in the injected fluid, but also constituents from the formation, which may include salts, metals, and radioactive elements. This recovered fluid is temporarily stored in tanks or lined pits. In some cases it may be reused for stimulating other wells, but often it requires treatment and disposal. Even with careful handling, the potentially large volume of recovered fluid increases the potential for uncontrolled surface releases that could enter the groundwater system if stored in surface pits. Risks include failures of the temporary storage units and releases during transport. The greatest risk to groundwater would be from storage of the fluid in large pits due the potentially large volume of fluid that could be released to the environment and the difficulty in detecting such leaks. Releases from storage tanks or tanker trucks would be less likely to be of sufficient volume and concentration to create a significant impact. Additionally, releases from storage tanks and tanker trucks would be easier to detect and stop then those from storage pits. | If a site-specific hydrogeologic assessment has not already been completed, perform a quick review of the hydrogeological system in the proposed gas well area performed to identify surface water bodies and water supply wells that might be impacted if releases should occur.<br><br>Monitor oil and gas activities as best possible for indications of improper handling or failed storage of recovered fluids and report them to the appropriate State authority. Since the shallow water system may quickly discharge to a nearby surface water body or water supply well that water body or well could be monitored for indications of changes in water quality. The simplest approach would be to measure for changes in field parameters such as conductivity and pH downstream/downgradient, adjacent to, and up stream/upgradient of the oil and gas activity. Ideally baseline values should be obtained before operations begin.<br><br>If state law requires fluid storage in aboveground storage tanks rather than storage pits, the risk will be considerably less, and will reduce the need for monitoring. |

**Table B-4 - Relative Risks to Groundwater from Oil and Gas Activity (from greatest to least)**

| Activity | Potential Risk | Potential Forest Service Actions |
|---|---|---|
| Groundwater pumping from shallow groundwater producing intervals | Each tight shale well requires approximately 1 to 6 million gallons of hydraulic fracturing fluid, which might be obtained from groundwater assuming the state permits it and that sufficiently productive water supply wells can be drilled nearby. Given the short-term nature of withdrawals (enough to fracture each well on the well-pad) there should be no long-term impacts, unless the same supply wells are being used to provide hydraulic fracturing water for a large number of gas wells. The greatest risk would be the temporary depletion of water to a nearby surface water body or groundwater dependent ecosystem if the water is withdrawn from the water table system, or to a nearby water supply well if the water is drawn from the same flow system. Depending on the sensitivity of the water body or ecosystem this may or may not be acceptable. In the area of the Wayne NF records from existing well logs indicate that groundwater is unlikely to be recovered in sufficient quantities to support tight shale hydraulic fracturing operations. Furthermore, it is understood the state does not allow use of local groundwater for hydraulic fracturing operations. | Assuming the state will permit it, if an operator is proposing to use shallow groundwater as a source of hydraulic fracturing water and a site-specific hydrogeologic assessment has not already been completed, perform a quick review of the hydrogeological system in the proposed gas well area performed to identify surface water bodies and water supply wells that might be impacted if releases should occur.<br><br>Monitor water levels in nearby surface water bodies, and in particular at the locations of sensitive ecosystems, for decreases that are not also observed in similar bodies located further away from the water well being used to supply the hydraulic fracturing operation.<br><br>If nearby wells (such as within a ¼ mile) producing from the same flow system are available, monitor water levels in them before, during and after water pumping.<br><br>If at all possible require or encourage the use (in descending order of preference) water supplies outside of the Forest, large water bodies, or groundwater producing intervals below those supplying surface water bodies or nearby water supply wells. |
| Improper well abandonment | Improperly abandoned oil and gas wells can be a serious source of groundwater contamination since the original casing and cement seal can degrade and corrode allowing formation fluids to leak into groundwater. Given greater regulation of well abandonment and improvements in well abandonment methods, this should seldom be of concern for new wells. However, many older abandoned wells likely were not adequately abandoned and pose a threat to groundwater quality. | There is little the Forest Service can do to ensure wells are properly abandoned except to inspect the well area following abandonment to see that the surface has been properly restored. Signs of questionable site restoration, which could also be an indication of improper well abandonment, may need to be reported to the BLM or State regulatory authorities.<br><br>If an orphan, abandoned well is discovered, have an evaluation of local hydrogeology, and if feasible, water quality at nearby receptors (springs, seeps, water supply wells) performed to evaluate if special action maybe needed to properly plug the well. |

## Table B-4 - Relative Risks to Groundwater from Oil and Gas Activity (from greatest to least)

| Activity | Potential Risk | Potential Forest Service Actions |
|---|---|---|
| Well failure | Failure of the oil or gas well casing or sealing cement around the casing could allow stimulation fluids and formation water to leak into a groundwater producing interval. This potential is reduced by the presence of at least two sets of casing and cement seals across the fresh water groundwater interval in typical well construction. Furthermore, the construction of a properly sealed well is critical to the success of a tight shale well with respect to natural gas or oil development. Therefore, it is in the interest of the operator to be sure the well has been properly constructed. | If a site-specific hydrogeologic assessment has not already been completed, perform a quick review of the hydrogeological system in the proposed gas well area performed to identify surface water bodies and water supply wells that might be impacted if releases should occur.<br><br>The operator should be able to identify well failure during the hydraulic fracturing operations. However, it may be too subtle to be immediately detected or may occur after hydraulic fracturing or other operations are completed. Monitoring of water quality in potentially affected surface water bodies and water supply wells might detect if groundwater is being impacted due to a well failure. |
| Groundwater pumping from deep groundwater producing intervals | Unless water is extracted from a single location to supply water for large numbers of tight shale wells, impacts to deep a groundwater producing interval will probably not be discernible and of much significance. This assumes that deep producing intervals with sufficient water of acceptable quality exist. Available information indicates that deeper groundwater may be too saline to use for hydraulic fracturing fluid, assuming sufficient production can be obtained from these intervals | Assuming the state will permit it, if an operator is proposing using deeper groundwater as a source of hydraulic fracturing water and a site-specific hydrogeologic assessment has not already been completed, perform a quick review of the hydrogeological system in the proposed gas well area performed to identify surface water bodies and water supply wells that might be impacted if releases should occur.<br><br>If nearby wells (such as within a ¼ mile) producing from the same groundwater producing interval are available, monitor water levels in them before, during and after water pumping.<br><br>If at all possible require or encourage the use of alternate water sources such as water sources outside of the Forest, large surface water bodies, or groundwater producing intervals located below those supplying surface water bodies or nearby supply wells. |

**Table B-4 - Relative Risks to Groundwater from Oil and Gas Activity (from greatest to least)**

| Activity | Potential Risk | Potential Forest Service Actions |
|---|---|---|
| Creation of fractures between the natural gas or oil formation and overlying potable groundwater | The hydraulic fracturing process is intended to increase the number of fractures within the producing formation just enough to allow economic recovery of natural gas or oil. The potential for these fractures to propagate into an overlying groundwater producing interval is highly unlikely, and depending on the distance and nature of the materials between the formation and overlying potable groundwater, may not even be physically possible. | No action recommended unless the oil producing formation is within a few hundred feet of an overlying potentially potable groundwater. This would not be expected with the tight shale beneath the WNF, as the formation is likely located 3,000 to 4,000 feet or more below the nearest potable groundwater.<br><br>Determine ahead of commencement of general drilling and hydraulic fracturing activities if targeted natural gas or oil producing formations beneath the NF are within a few hundred feet of potentially potable groundwater. This information should be obtainable from available sources.<br><br>If they are, perform monitoring as recommended for potential well failure, if feasible. |